
17. EDUCATIONAL GAMES AND SIMULATIONS: A TECHNOLOGY IN SEARCH OF A (RESEARCH) PARADIGM

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17.1 INTRODUCTION

Educational games and simulations, unlike direct forms of instruction, are experiential exercises. That is, student teams may be racing each other to reach a pot of gold (game), sifting through an archeological site and analyzing the artifacts (simulation), or managing a financial institution for several months (simulation).

Games and simulations entered the broad educational scene in the late 1950s. Until the early 1970s, they were not part of the instructional design movement. Instead, these exercises were primarily developed by business and medical education faculty and sociologists who adapted instructional developments pioneered by the military services. Although popular in the public schools in the 1960s, games and simulations in United States classrooms declined with the advent of the basic-skills movement.

Currently, the increased power and flexibility of computer technology is contributing to renewed interest in games and simulations. This development coincides with the current perspective of effective instruction in which meaningful learning depends on the construction of knowledge by the learner. Games and simulations, which can provide an environment for the learner's construction of new knowledge, have the potential to become a major component of this focus.

The technology, however, faces two major problems at present. One is that comprehensive design paradigms derived from learning principles have not been available. Coupled with the variety of disciplines attempting to develop games and simulations, the result is a variety of truncated exercises often mislabeled as simulations. One study, for example, referred to a static computer graphic of a pegboard as a simulation. Another study that purported to be a simulation of decision making was a series of test questions about different situations in which the student was to assume that he or she was an administrator of special education. A third "simulation" simply provided preservice teachers practice in

completing classroom inventory forms, supply requisition forms, and incident reports. These latter two examples are context-based problems, but they are not simulations.

These mislabeled exercises indicated the need for effective design models for games and simulations. Design models are the "soft technologies" that influence and activate the thought processes of the learners rather than the "hard technology" of the computer (Jonassen, 1988). Also, poorly developed exercises are not effective in achieving the objectives for which simulations are most appropriate—that of developing students' problem-solving skills. Finally, poorly developed games and simulations often have negative effects on students, some of which are discussed later in the chapter.

The second major problem for developers and users of games and simulations is the lack of well-designed research studies. Much of the published literature consists of anecdotal reports and testimonials. These discussions typically provide a sketchy description of the game or simulation and report only perceived student reactions.

Further, as indicated by Pierfy (1977), most of the research is flawed by basic weaknesses in both design and measurement. Some studies implemented games or simulations that were brief treatments of 40 minutes or less and assessed effects weeks later on midterm or final examinations. Intervening instruction, however, contaminates the results.

Another major design weakness is that most studies compare simulations to regular classroom instruction (lecture and/or classroom discussion). However, the instructional goals for which each can be most effective often differ. The lecture method is likely to be superior in transmitting items of information. In contrast, simulations have the potential to develop students' mental models of complex situations as well as their problem-solving strategies. Not surprisingly, a meta-analysis of 27 research studies (for the period 1969–1979) that met basic validity and reliability criteria found that simulations were not superior to lecture or discussion on information-oriented posttests (Dekkers & Donatti, 1981).

Among the measurement problems in reported studies is the failure to describe the nature of the posttests used to measure student learning. Some studies use essay questions, while others use some type of instructor-developed test with no reported validity or reliability information. In addition, some researchers provided the simulation group with additional problems to solve or information summaries that the other group did not receive.

Another problem is that comparison studies often are not sensitive to the student characteristics that interact with instruction to influence achievement. One study by Wentworth and Lewis (1973) identified three characteristics that mediated the instructional effects of a commercially developed simulation for junior college students in economics. Formulation of a stepwise regression model to identify the variables that predict achievement indicated that prior knowledge, ability, and the school attended were significant contributors to posttest achievement on a standardized economics test for students in the course-related simulation. In other words, like other forms of instruction, simulations and games are likely to be more effective with some students than with others.

Finally, the classroom research paradigm implemented in the 1960s and 1970s did not document the actual instructional processes associated with an innovation. Instead, the innovation was assumed to differ substantially from typical classroom instruction, and the innovation was compared with traditional practice. Subsequent analyses of the 1970s classroom research has indicated that, in many cases, instruction in the comparison classes shared key characteristics with the innovative classes (see House et al., 1978; Glass, 1979; Hall & Loucks, 1977). The result was a "no significant difference" finding in these comparisons.

Like other classroom research, studies that addressed games and simulations did not document the ways that students interacted with the subject matter and each other during a game or simulation. For example, although simulations are described as enhancing decision making, key questions unasked by the research are: For which student and in what ways? What tradeoffs between increased decision making and information load? And so on. At present, a few studies are beginning to investigate the dynamics of student interactions with games and simulations, and this research and the implications for design are discussed in this chapter.

Given the issues facing the gaming and simulation field, the purpose of this chapter is threefold. The chapter first presents and discusses a definitive framework for games and simulations that addresses the essential features of each type of exercise. Then the chapter discusses the research studies that have implications for instructional design. The chapter concludes with a discussion of recommended guidelines for research on games and simulations.

17.2 A DEFINITIVE FRAMEWORK

Games and simulations are often referred to as *experiential exercises* because they provide unique opportunities for students to interact with a knowledge domain. Two con-

cepts important in the analysis of the nature of games and simulations are surface structure and deep structure. Briefly defined, *surface structure* refers to the paraphernalia and observable mechanics of an exercise (van Ments, 1984). Examples in games are drawing cards, moving pieces around a board, and so on. An essential surface structure component in a simulation, in contrast, is a scenario or set of data to be addressed by the participant.

Deep structure, in contrast, may be defined as the psychological mechanisms operating in the exercise (Gredler, 1990, 1992a). Deep structure refers to the nature of the interactions (1) between the learner and the major tasks in the exercise, and (2) between the students in the exercise. Examples include the extent of student control in the exercise, the learner actions that are rewarded in the exercise or which receive positive feedback, and the complexity of the decision sequence in the exercise (e.g., linear or branching).

17.2.1 Deep-Structure Characteristics

A shared feature of games and simulations is that they transport the players (game) or participants (simulation) to another world. For example, children may be searching for vocabulary clues to capture a wicked wizard (game), and medical students may be diagnosing and treating a comatose emergency room patient (simulation).

Another similarity is that, excluding adaptations of simple games like Bingo, games and simulations are environments in which students are in control of the action. Within the constraints established by the rules, game players plan strategy in order to win, and simulation participants undertake particular roles or tasks in order to manage an evolving situation. Examples of evolving situations are managing a business and designing and managing research projects on generations of genetic traits.

The deep structure of games and simulations, however, varies in three important ways. First, games are competitive exercises in which the objective is to excel by winning. Players compete for points or other advances (such as moving forward on a board) that indicate they are outperforming the other players. In a simulation, however, participants take on either (1) demanding, responsible roles such as concerned citizens, business managers, interplanetary explorers, or physicians, or (2) professional tasks such as exploring the causes of water pollution or operating a complex equipment system. In other words, instead of attempting to win, participants in a simulation for the classroom are executing serious responsibilities, with the associated privileges and consequences. Jones (1984, 1987) refers to this characteristic of simulations as "reality of function."

A second difference is that the event sequence of a game is typically linear, whereas a simulation sequence is nonlinear. The player or team in a game responds to a stimulus, typically a content-related question, and either advances or does not advance, depending on the answer. This sequence is repeated for each player or team at each turn.

In a simulation, however, participants at each decision point face different problems, issues, or events that result in large measure from their prior decisions. In a computer-delivered simulation, this feature is referred to as *branching*.

A third difference between simulations and games is the mechanisms that determine the consequences to be delivered for different actions taken by the students in the exercise. Games consist of rules that describe allowable player moves, game constraints and privileges (such as ways of earning extra turns), and penalties for illegal (nonpermissible) actions. Further, the rules may be imaginative in that they need not relate to real-world events. In contrast, the basis for a simulation is a dynamic set of relationships among several variables that (1) change over time and (2) reflect authentic causal processes (i.e., the relationships must be verifiable). For example, in diagnostic simulations in which the student is managing the treatment of a patient, the patient's symptoms, general health characteristics, and selected treatment, all interact in predictable ways.

In addition to these three general characteristics, particular games and simulations also differ in the tasks established for students and the actions that are rewarded in the exercise. These specific differences are discussed later in the chapter.

17.2.2 Experiential and Symbolic Simulations

The broad category of instructional simulations consists of two principal types. One type, referred to as *experiential simulations*, establishes a particular psychological reality and places the participants in defined roles within that reality. The participants, in the context of their roles, execute their responsibilities in an evolving situation. Experiential simulations, in other words, are dynamic case studies with the participants on the inside (see 23.4.2).

Essential components of an experiential simulation are (1) a scenario of a complex task or problem that unfolds in part in response to learner actions, (2) a serious role taken by the learner in which he or she executes the responsibilities of the position, (3) multiple plausible paths through the experience, and (4) learner control of decision making (see Chapter 33).

Experiential simulations originally were developed to provide learner interactions in situations that are too costly or hazardous to provide in a real-world setting. Increasingly, however, they have begun to fulfill a broader function, that of permitting students to execute multidimensional problem-solving strategies as part of a defined role. The need for such exercises is indicated by several studies. For example, Willems (1981) found that students in law, social geography, science, and sociology often are unable to apply knowledge they had acquired to the task of solving problems. Further, de Mesquita (1992) found that 53% of school psychology students and graduates initially made an incorrect diagnosis in a school-referral problem involving a third-grader.

Experiential simulations are designed to immerse the learner in a complex, evolving situation in which the learner

is one of the functional components. The advent of computer technology, however, made possible the design of a different type of interaction exercise: a symbolic simulation. Briefly, a symbolic simulation is a dynamic representation of the functioning or behavior of some universe, system, set of processes, or phenomena by another system (in this case a computer). The behavior that is being simulated involves the interaction of two or more variables over time.

A key characteristic of symbolic simulations (like experiential simulations) is that they involve the dynamic interactions of two or more variables. An example of a symbolic simulation is a population-ecology simulation with 75 variables that represents global ecological processes for the 200-year period after 1900 (Forrester, 1971; Hinze, 1984). Another is a dynamic computer representation of a complex equipment system. The student, interacting with a symbolic simulation, may be executing any of several tasks, such as troubleshooting equipment or predicting future trends. However, the student remains external to the evolving events. Many computer exercises erroneously labeled as simulations do not meet this criterion, and this shortcoming arises from the misapplication of the term *simulated*. For example, simulated diamonds are imitation diamonds. Extrapolation of this concept to instructional development has led to the erroneous designation of imitations of objects or events as "simulations." An example is a brief Apple II computer program that purports to simulate plant growth. However, the program only presents an outline of a two-leaved plant that shoots up faster, slower, or not at all, depending on whether the student selects "full light," "half light," or "no light." The motion of the stilted graphic is a highly simplistic imitation of plant growth, but it is not a simulation. In other words, an animated graphic of some event is not necessarily a simulation.

Symbolic simulations differ from experiential simulations in two major ways. First, the learner is not a functional element of the situation. Instead, symbolic simulations are populations of events or interacting processes on which the learner may conduct any of several different operations. In other words, the deep structure of symbolic simulations is that the learner manipulates variables that are elements of a particular population. The purpose is to discover scientific relationships or principles, explain or predict events, confront misconceptions, and others. Potential instructional purposes for symbolic simulations are described by Riege-luth and Schwartz (1989) as explanation, prediction, solution, or procedure. Tennyson et al. (1987) differentiate simulations as task oriented or problem oriented.

The second major difference is the mechanisms for reinforcing appropriate student behaviors. The learner in an experiential simulation steps into a scenario in which consequences for his or her actions occur in the form of (1) other participants' actions or (2) changes in (or effects on) the complex problem that the learner is attempting to manage. The learner who is executing random strategies often quickly experiences powerful contingencies for such behavior, from the reactions of other participants to being exited from the simulation for inadvertently "killing" the patient.

The symbolic simulation, however, is a population of events or set of processes external to the learner. That is, there is not an assigned role that establishes a vested interest for the learner in the outcome. Although the learner is expected to interact with the symbolic simulation as a researcher or investigator, the exercise, by its very nature, cannot divert the learner from the use of random strategies.

One solution is to ensure, in prior instruction, that students acquire both the relevant domain knowledge and essential research skills. That is, students should be proficient in developing mental models of complex situations, testing variables systematically, and revising one's mental model where necessary. In this way, students can approach the symbolic simulation equipped to address its complexities, and the possibility of executing random strategies holds little appeal.

Table 17-1 summarizes the primary characteristics of games, experiential simulations, and symbolic simulations. Specific design rules and subtypes are discussed in the following sections.

17.3 ACADEMIC GAMES

As already indicated, games are competitive contests characterized by discrete plays or moves by the players. The objective is to win by any strategy permitted by the rules. Of importance in selecting games for classroom use are

particular characteristics of the deep structure of the exercise. First, academic games should not sanction strategies that involve questionable ethics. The deep structure of Monopoly, for example, is such that a player is reinforced by attempting to bankrupt other players. Although an acceptable practice in a parlor game, reinforcing student strategies designed to bankrupt others is not appropriate in the public school classroom.

The deep structure of academic games should meet two requirements. First, chance or random factors should not contribute to winning. For example, some poor examples of computer games purport to develop students' spatial skills. However, they are merely two-dimensional puzzles that may be solved by guessing (Edens & Gredler, 1990).

Second, winning in academic games should depend solely on the application of subject-matter knowledge and/or problem-solving skills. Given this characteristic, games may be used for any of four general purposes in the classroom. They are (1) to practice and/or to refine knowledge/skills already acquired, (2) to identify gaps or weaknesses in knowledge or skills, (3) to serve as a summation or review, and (4) to develop new relationships among concepts and principles.

The academic skills that contribute to challenging classroom games are the intellectual skills (see 18.3.3) identified by Gagné (1977, 1985). They are discriminating, such as matching chemical formulas to names; concept learning, such as classifying paintings into styles or periods; and rule using, such as predicting consequences from events.

TABLE 17-1. PRIMARY CHARACTERISTICS OF GAMES AND SIMULATIONS

	Games		Simulations	
			Experiential	Symbolic
<i>Setting:</i>				
Students are transported to another world or environment	X		X	X
<i>Purpose:</i>				
Competition and winning	X			
Fulfilling a professional role			X	
Executing a professional task				X
<i>Event sequence:</i>				
Typically linear	X			
Nonlinear or branching			X	X
<i>Mechanisms that determine consequences:</i>				
Sets of rules (may be imaginative)	X			
Dynamic set of authentic causal relationships among two or more variables			X	X
Participant is a component of the evolving scenario and executes the responsibilities of his or her role			X	
Participant interacts with a database or sets of processes to discover scientific principles, explain or predict events, and confront misconceptions				X

One key characteristic of games is that, during the exercise, they alter two aspects of the classroom reward structure. They are the frequency of reinforcement and the immediacy of feedback (DeVries & Edwards, 1973). The player or team that successfully responds to the game stimulus, typically an academic question or problem, is reinforced immediately by advancing in the game. The student or team decision that is incorrect receives immediate feedback by not advancing in the exercise.

Manual games are limited in the amount and extent of feedback they can provide for learner actions. The data-processing capability of the computer, however, makes possible the development of sophisticated games in which students apply a broad base of knowledge to solve complex problems. A rare example of this type of game requires the student to apply his or her knowledge of social and economic institutions in 17th-century France to improve the social standing of a Frenchman of that century (Lougee, 1988). At each turn, the student has several options, such as attempting to establish a marriage contract, buying and selling grain, leasing land, and so on. The computer evaluates each choice made by the player and maintains a running score in the form of a social index.

Success in such a game requires players to direct and manage their thinking in an efficient and effective manner. Variables must be noted, likely consequences of actions must be considered in advance, and then a course of action must be developed. These capabilities are of the type referred to by Gagné (1977, 1985) as *cognitive strategies*. Thus, one advantage of computer games is that they have the potential to challenge students' thinking in a variety of ways.

17.4 EXPERIENTIAL SIMULATIONS

Like the player in an academic game, the participant in a simulation also applies a knowledge base. However, the simulation participant is facing a complex situation in which he or she is one of the components. Further, the situation evolves and changes in part in response to the participant's decisions and actions.

Within the category of experiential simulations, exercises may differ in (1) the nature of the participants' roles, (2) the types of decisions and interactions in the exercise, and (3) the nature of the relationships among the variables. That is, experiential simulations may be individual or group exercises, the focus may vary from executing professional expertise to experiencing a different cultural reality, and the relationships among the variables may be quantitative or qualitative. Four major types of experiential simulations are data management, diagnostic, crisis management, and social-process simulations (Gredler, 1992a).

17.4.1 Data Management Simulations

A participant in a data management simulation typically functions as a member of a team of financial managers or planners. Each team that is managing a company or institu-

tion allocates economic resources to any of several variables in order to achieve a particular goal. The long-range goal is to improve the status of the institution or company (Gredler, 1992a).

The simulation typically encompasses 12 to 18 business quarters (rounds) in which each team makes several short- and long-term investment and budgeting decisions. At the end of the business quarter (from 45 minutes to 2 to 3 hours), the decisions are analyzed by the computer, and each team receives an updated printout that indicates their institution's financial standing. The team analyzes the printout and makes the next set of decisions.

Although the team members interact in making decisions, the primary focus in data management simulations is on the interrelationships and trade-offs among quantifiable variables. In a bank management simulation, for example, participants are expected to address the relationships among profitability, liquidity, and solvency, and between profits and volume of business (Galitz, 1983).

Data management simulations are based on mathematical models that adjust parameter values as student inputs are made. The simulation designer specifies the set of equations that reflects the relationships among the variables. Depending on the complexity of the situation, the number of required equations may range from half a dozen to over 50.

17.4.2 Diagnostic Simulations

Originating in medical education, diagnostic simulations are currently found primarily in several health care fields, education, and psychology. Some diagnostic simulations are team exercises that require the discovery, evaluation, and interpretation of relevant data, as in an air accident investigation (Rolfe & Taylor, 1984). In the majority of examples, however, a student takes the role of a physician, nurse, psychologist, or teacher. The student selects and interprets data and selects corrective actions in the diagnosis and management of the patient's or client's problem.

The deep structure of diagnostic simulations consists of an evolving problem that requires sequential interrelated decisions. The sequential nature of the task links each decision to prior decisions and results. Therefore, as in real situations, errors may be compounded on top of errors as nonproductive diagnostic and solution procedures are pursued (Berven & Scofield, 1980).

Key components of diagnostic simulations are a sketchy description of a multifaceted problem, the prescribed role of the participant, and multiple plausible alternatives at each decision point (McGuire, Bashook & Solomon, 1976). Also, the problems are those that involve the consideration of more than a simple cause. Thus, they are not textbook problems. In an air accident investigation, for example, contributing factors are both human and mechanical (Rolfe & Taylor, 1984).

Of major importance is that the student who is unsure of the appropriate course of action can find plausible choices. The only feedback received by the student during the exercise is either the data he or she requested or the effects of a

selected action on the situation. Further, the complications that the student must address will vary depending on his or her unique pattern of decisions (McGuire et al., 1976). Thus, a major purpose of many diagnostic simulations is to obtain a record of the student's progress through the multiple possible paths so as to differentiate adequate problem solvers from the students using ineffective approaches.

Figure 17-1 illustrates the various paths through a simulation for the diagnosis and management of a patient. Each of the major strategy decisions, e.g., take history, obtain laboratory data, and so on, is represented by a box on the simulation map. Within the major strategy choices, students may select from a number of plausible specific decisions. The map indicates the decisions to be made and those to be avoided, according to a panel of experts. Solid arrows indicate the route recommended by a panel of experts. As indicated by the map, the student is not terminated from the simulation unless he or she takes action that causes the patient's death.

Early examples of diagnostic simulations for individual students were multiple-branching exercises in booklet form. They have since been replaced by computer-delivered exercises, some of which accept voice input (see Ditlehorst & Barrows, 1982; Pickell et al., 1986).

17.4.3 Crisis Management Simulations

A crisis management simulation begins with an unexpected event that threatens the welfare of an individual or a group and which must be quickly resolved. Key components of crisis-management simulations are the rapidly increasing time pressure and the need to prevent a major disaster of some sort.

Both political-crisis exercises, in which a country's security or welfare is threatened, and combat simulations are examples. Political-crisis exercises involve a small team of decision makers representing each country and interacting in a compressed time frame. Combat simulations used for training are either individual or team exercises, and these simulations have been revolutionized by advanced computer technology. Large-scale field maneuvers used to educate commanders and their staffs and some weapons systems training are currently conducted with discrete and networked computer simulations (Oswalt, 1993). A current project is creating a simulated environment that will permit military personnel to view the battlefield in three dimensions, including the capability to reconnoiter the terrain (Oswalt, 1993, p. 154).

17.4.4 Social-Process Simulations

The focus of data management, diagnostic, and crisis management simulations is on a complex task or problem in which human interactions play minor roles, if at all. The student behaviors of primary interest are the decisions made to

address a complex cognitive problem. In contrast, the deep structure of social-process simulations is the interactions among the participants and the ways that one's beliefs, assumptions, goals, and actions may be questioned, hindered, or supported in interactions with others (Gredler, 1992a). Goals of social-process simulations are (1) to develop an understanding of a particular social organization or culture, (2) to help develop abilities to think and communicate in an unfamiliar situation (Jones, 1982), or (3) to help develop empathy for others by experiencing an aversive situation as others would, followed by reviewing and discussing one's beliefs and assumptions (Thatcher, 1983; Thatcher & Robinson, 1990).

Participants typically take roles with different interests, priorities, and responsibilities in one of the groups faced with conflicting issues or tasks. Among the examples of social-process simulations are (1) an economically deprived region that must address a proposed tourism development that will also have some negative effects, and (2) the writing, editing, and broadcasting of a radio news program as items continue to come in until air time.

Key components of social-process simulations are (a) a precipitating event or key task, (b) well-defined participant roles, (c) complicating factors, and (d) context (Gredler, 1992a). All of these components interact with each other to set in motion the interactions among participants that are the core of the simulation. Of major importance is that each role (1) must have a stake in the outcome of the exercise and (2) be one to which the participant can commit his or her thoughts and feelings; that is, the role must generate "reality of function."

17.4.5 Discussion: Experiential Simulations

Experiential simulations vary widely in the type of experience established for the learner and the type of causal model underlying the exercise. Data management simulations are most often team exercises in which the relationships among the variables to be manipulated are specified by sets of mathematical equations—a quantitative causal model (see Table 17-2).

In contrast, diagnostic, crisis management, and social-process simulations are based on qualitative causal models. That is, cause-effect contingencies are drawn from actual cases, and the optimal route through the simulation is verified by experts who are asked to work through the exercise. Social-process exercises, however, depend on the interactions of individuals as they react to different situations. Unless contingencies for different actions have been carefully embedded in the context and various roles, the exercise can take unexpected directions.

Of the four types, only the diagnostic simulation can be computer based. Decisions in the other types typically require team decision making, and computers cannot replicate social situations (Crookall, Coleman & Oxford, 1992).

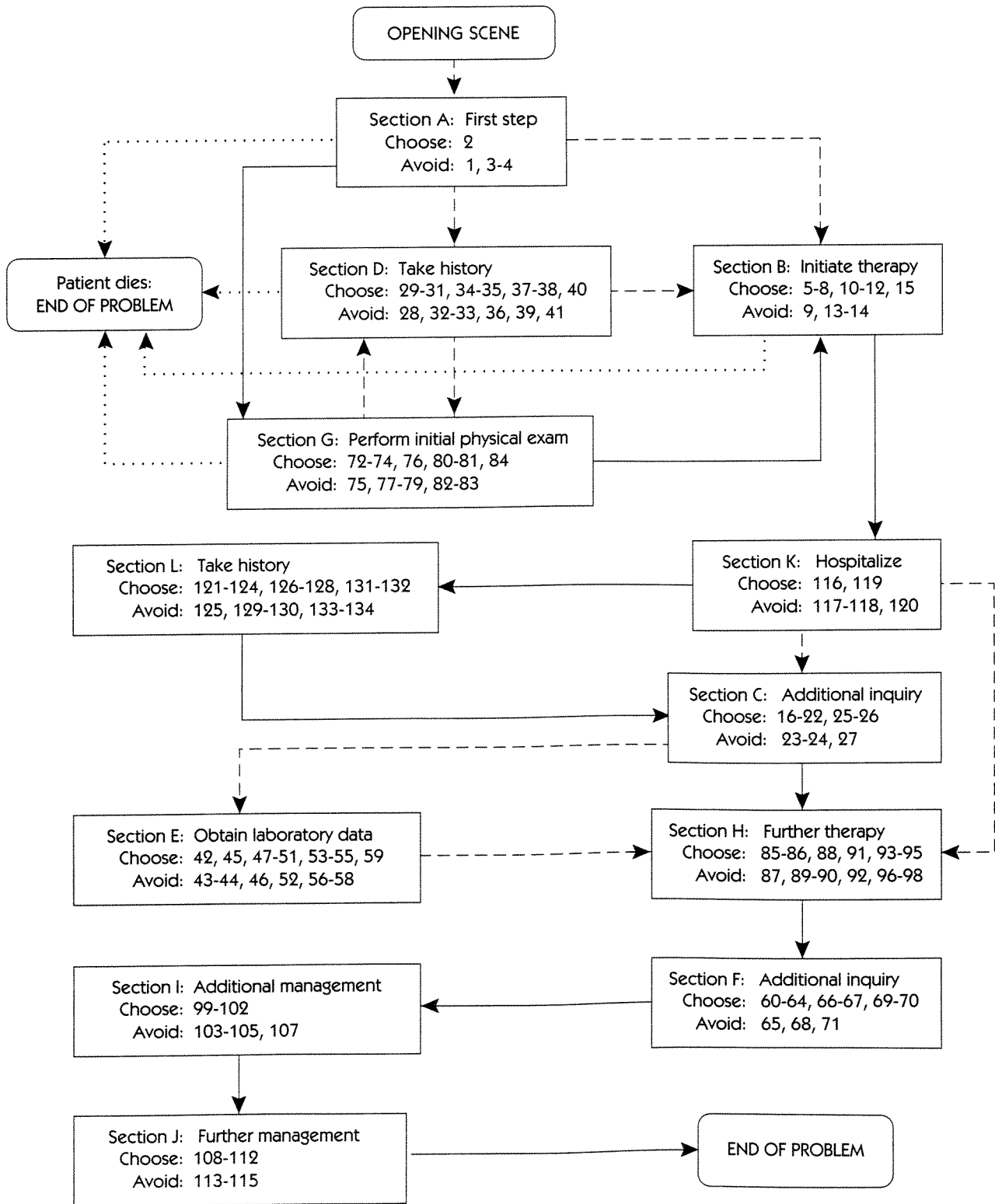


Figure 17-1. Map of a simulation to diagnose and manage patient SL. Numbers in boxes refer to items to be chosen and to items to be avoided. Solid arrows indicate the route recommended by a panel of experts. Dashed arrows indicate alternate path; solution still possible. Dotted arrows indicate path to unsatisfactory termination. (Reprinted by permission of the Psychological Corporation.)

TABLE 17-2. SUMMARY OF EXPERIMENTAL SIMULATIONS

Type	Structure	Underlying Model	Task
Data management	Successive rounds of decision making; typically team based	Quantitative	Allocate economic resources to any of several variables to improve status of the institution or company
Diagnostic	An evolving complex problem that requires sequential interrelated decisions; typically an individual exercise	Qualitative	Select and interpret data and implement strategies in order to manage a complex, evolving problem
Crisis management	An escalating situation that threatens the welfare of a group or individual; may be individual or team based	Qualitative	Resolve the escalating situation under increasing time and other pressures
Social-process simulations	The interaction of a precipitating social task or event, well-defined participant roles, complicating factors, and context; team-based exercise	Qualitative	Resolve a social problem or issue that is accompanied by different priorities or goals of the associated roles

However, computer analyses of data generated by team members often serves as input to participant decisions.

Experiential simulations share several key characteristics. First, the learner is a functional component of the situation and experiences it from the inside. Second, the learner takes on serious responsibilities as a participant in an ongoing fluid situation. Third, the intent is for the participant to experience the effects of his or her decisions; i.e., the student's discipline problem becomes worse, a proposed compromise is repealed, and so on. Finally, experiential simulations also can provide opportunities for students to develop their cognitive strategies because the exercises require that they organize and manage their own thinking and learning.

17.5 SYMBOLIC SIMULATIONS

In contrast to experiential simulations, a symbolic simulation is a dynamic representation of the functioning or behavior of some universe, system, set of processes, or phenomena by another system (in this case, a computer). In other words, symbolic simulations are populations of events or sets of interacting processes. The role of the learner in relation to a symbolic simulation is typically that of a researcher or investigator. That is, the learner manipulates different variables in order to discover scientific relationships, explain or predict events, or confront misconceptions.

Symbolic simulations may be classified according to the nature of the variables and the nature of the interactions among them. Four types of symbolic simulations are cur-

rently in use that differ in these characteristics. They are data-universe simulations, system simulations, process simulations, and laboratory-research simulations.

17.5.1 Data Universe Simulations

A data universe simulation represents the behavior of sets of related elements that compose a population of continuing events. The simulation expresses the relationships among the variables through the use of mathematical equations. An example is the population ecology simulation described earlier. The simulation illustrates the effects of the 75 variables on population, capital investment, food production, pollution, and quality of life (Forester, 1971; Hinze, 1984). The output is a graph that illustrates the effects of continued turn-of-the-century trends on the five characteristics of civilizations. Trends also may be altered by the user and the effects observed.

The situation typically posed for the student in a data universe simulation is to test student-generated hypotheses about a large population of interrelated variables and outcomes. The goal is to discover relationships or trends among the variables. The purpose of a data universe simulation typically is to provide students with opportunities to discover scientific laws and principles, such as the laws of genetics (see 24.9 for a discussion of databases and cognitive tools).

Note that data universe simulations differ from other simulations that involve the manipulation of variables. First, students are functioning as researchers by testing their own

hypotheses, reviewing the outcomes, and testing new hypotheses or continuing their research strategy. In other interactive exercises, students are often attempting to solve a problem that has been posed for them and/or they are working with a smaller database. For example, in a data management simulation, the student is executing specific role-related responsibilities in which the goal for the student or the team is to enhance the economic status of an institution or enterprise.

17.5.2 System Simulations

A system simulation demonstrates the functional relationships between the components of a physical or biological system (such as a small ecosystem) or a constructed system (such as complex equipment systems). Students learn about the particular system or solve problems involving the system by manipulating the components.

One important role for the interactive graphics and videodisc capability of current computer technology is to provide functional representations of complex systems that students can operate. An example is the steam plant system and subsystems developed for the U.S. Navy known as *STEAMER*. The exercise also includes a quantitative component so that the student can open and shut valves, turn components on and off, adjust throttles, and observe the effects on indicators, such as dials, thermometers, and digital readouts (Stevens & Roberts, 1983).

System simulations are often used to teach the operational principles of complex equipment composed of subsystems. They also are used to teach procedures and may, depending on the design of the simulation, develop students' cognitive strategies. The use of a simulation to teach maintenance procedures, for example, is the procedural simulation referred to by Riegeluth and Schwartz (1989).

Examples that develop students' cognitive strategies are the low-cost plywood M1 tank simulators and M2/3 fighting vehicles, each with its own microprocessor database of the terrain, graphics, and sound system developed in project SIMNET. Each "armored vehicle" is a system that generates the battle engagement environment required for the combat mission training of its crew. Each crew member sees a part of the virtual world defined by his line of sight (e.g., forward for the driver) (Alluisi, 1991, p. 350).

17.5.3 Process Simulations

The focus of a process simulation is a naturally occurring phenomenon in the physical, chemical, or biological realm (Riegeluth & Schwartz, 1987). Interactive graphics images can illustrate processes that are unobservable and/or are not easily experimented with in the classroom. Students can manipulate variables and attempt different tasks in order (1) to discover the relationships among the variables or (2) to confront their misconceptions.

Confronting student misconceptions about Newtonian mechanics is the goal of several process simulations devel-

oped in physical science (Flick, 1990; White, 1984). DiSessa (1982, 1985) and others note that students' intuitive knowledge about force, motion, and velocity derived from experience in a gravity-bound world often prevents students' construction of accurate mental models of physics principles. White (1984, 1995), for example, has designed several progressively more difficult gamelike tasks that require the student to perform several actions on a "spaceship" in a frictionless environment (space). Force, velocity, and speed are illustrated in the interactive exercises.

DiSessa (1982) identifies three important contributions of process simulations that represent physics principles. First, they provide students an opportunity to interact with phenomena at a qualitative level. Often, students only interact with quantitative problems in which getting the right answer typically becomes their goal. Second, students' fragmented and often naive knowledge of phenomena is challenged. Third, simulations can change the time scale of exercises from the 20 minutes or so per type to problems that can engage students in investigations that can span days or weeks.

17.5.4 Laboratory Research Simulations

Laboratory-research simulations are specific to courses that include laboratory sessions as part of the course work. Among them are biology, chemistry, physics, and, occasionally, physical science. These exercises provide visual and graphic components for students to manipulate, and they illustrate the results. Early examples of chemistry experiments used color microfiche images projected onto the back of a plasma panel with a PLATO IV system (Smith & Sherwood, 1976). Currently, computer laboratory simulations are making use of videodisc technology to expand the range and complexity of the experiments conducted by students.

These simulations differ from data-universe and process simulations in that they are a series of discrete problems. Because laboratory research exercises are a series of discrete experiments instead of a complex evolving problem, they are categorized by some theorists as problem-solving exercises in a simulated context (Gredler, 1992a). Nevertheless, the computer videodisc simulations provide realistic experimental reactions. Further, students can conduct experiments that involve hazardous or costly materials. Also, slow reactions that students may not ordinarily be able to observe may be sped up (and others may be slowed down). Moreover, experiments can be repeated (Smith & Jones, 1989).

17.5.5 Discussion: Symbolic Simulation

Symbolic simulations may be developed at any of several different levels of complexity. Data universe simulations are the most complex, in which a large population of events is represented and the causal models are quantitative. System simulations are less broad and may involve either quantitative or qualitative models of causality. Process simulations, in contrast, typically address specific interactive

processes in the physical world that are often poorly understood by students. In addition to biological processes, the interactions of variables such as force, speed, and velocity are typical examples. Causal models for process simulations also may be quantitative or qualitative. Laboratory research simulations, in contrast, involve a series of discrete activities that are directed by students. Again, the causal models for the specific experiments may be quantitative or qualitative (see Table 17-3).

17.6 INSTRUCTIONAL DESIGN IMPLICATIONS DERIVED FROM RESEARCH

Many classroom games and simulations are developed for a particular class, and the key design variables often are not explicitly identified. Further, much of the research has investigated "variables of convenience," i.e., attitudes and content-related achievement (Wentworth & Lewis, 1972). Nevertheless, a few studies have investigated other effects of games and simulations that have implications for design.

17.6.1 Academic Games

One of the stated requirements for academic games is that advancement in the exercise and winning should be based on academic skills. A study conducted by Schild (1966) tested the premise that students learn those skills and strategies that are reinforced by the structure of the game, i.e., the skills essential for winning. He recorded the decisions made by four groups of players of the Parent-Child game, in which pairs composed of one parent and one child must negotiate appropriate child behaviors on five issues. The

"child" can damage the "parent's" score through consistent delinquency, and the "parent" can damage the "child's" score by excessive control and punishment. However, by round 4 of the game, most players had learned the optimal strategy essential to maximizing both the parent and child scores for their team. In other words, the teams had learned the optimal strategy for winning. The implication for game design is that game structure should be carefully constructed so that winning depends on strategies acceptable in the classroom and knowledge in the subject area.

Several studies on the classroom game Teams-Games-Tournaments (TGT) have implications for game design. A unique feature of TGT is that it alters both the task and reinforcement structure of the classroom. Most classrooms are highly competitive, with individual students competing for scarce reinforcements (DeVries & Edwards, 1973; DeVries & Slavin, 1978). In contrast, TGT introduces a cooperative task structure within teams and increases greatly the availability of reinforcement.

TGT organizes the class into teams of comparable achievement (e.g., one high achiever, two average achievers, and one low achiever), but each student competes at a three-person tournament table with students at the same ability level. Each student's score contributes to the overall team score. (Scores earned at the tournament are 6 points, high scorer; 4 points, middle scorer; and 2 points, low scorer.) Practice sessions also are scheduled a few days prior to the weekly or biweekly tournament.

Because the team score is dependent on the performance of all the team members, the game structure reinforces peer tutoring and cooperative learning during the practice sessions. In one study, the games/teams combination increased the amount of peer tutoring beyond that in either games/indi-

TABLE 17-3. SUMMARY OF SYMBOLIC SIMULATIONS

Type	Structure	Underlying Model	Task
Data universe	Represents a large population of events; may be individual or team based	Quantitative	To develop mental models about the interrelationships of variables and test the models
System	Demonstrates the functional relationships between the components of a physical or biological system or a constructed system (such as complex equipment systems)	Quantitative or qualitative	To explain or predict events in the system
Process	Represents specific interactive processes in the physical world	Quantitative or qualitative	To discover relationships among the variables and/or to confront misconceptions
Laboratory research	A series of student directed discrete experiments in simulated environments	Quantitative or qualitative	To become proficient in conducting specific experiments, documenting results, and conclusions

vidual reward or quizzes/team reward classes (DeVries & Edwards, 1973). Classes that participated in TGT (team reward) also perceived a decrease in both classroom competitiveness and course difficulty (measured by the Learning Environment Inventory, LEI). The researchers suggest that these perceptions are the result of the task interdependence of the game and the increased opportunities for reinforcement.

A review of 10 studies in which TGT was implemented in mathematics, language arts, and social-studies classes indicated consistent effects on achievement (measured by standardized tests) and mutual concern (measured by questionnaire scales adapted from the Learning Environment Inventory). Some of the studies compared TGT to regular classroom instruction, and others compared TGT to the traditional classroom and a modification of TGT in which higher- or lower-scoring students' scores were weighted more heavily. However, the modifications did not produce a greater effect on achievement than the original TGT.

Of importance for game design in general is the relationship between competition and cooperation. Competition is the essence of any game. However, the mutual dependence of students on each other reinforces cooperation, an important characteristic of a positive classroom environment.

17.6.2 Computer Games

A key issue in manual games is the influence of a game on classroom dynamics. In contrast, key issues in computer-delivered games are the mechanics of play and the observance of accepted instructional design principles. Many computer-delivered games, however, have not been developed by instructional designers. Instead, like the programmed instruction movement of the 1960s, various other groups have developed many of the products. Often, the computer software has not undergone formative or summative evaluation. Although reviews of software are available, few reviewers implement the materials with students. Moreover, evaluation checklists do not require the reviewer to conduct observations of student use (Vargas, 1986).

Observations of students using computer software indicate some problems with computer games in both game mechanics and principles of instructional design (Vargas, 1986; Gredler, 1992a). Briefly summarized, the game mechanics problems include inappropriate vocabulary for young students, inadequate directions, lengthy texts, and multistep directions with no opportunity for student practice and inappropriate use of graphics (Vargas, 1986; Gredler, 1992a). In addition, computer games often do not provide options for students to bypass tasks that are too complex or bypass items they are unable to answer. Since the only way for the player to continue in the game is to strike a key or type in a word, players are forced to enter random answers, which, of course, are evaluated by the computer as wrong (Gredler, 1992a).

In addition to the mechanics of play, frequent observations of students using computer software indicate two

instructional design problems. They are (1) inadequate stimulus control and (2) defective reinforcement contingencies. For example, the use of a question with several possible answers in which only one answer is accepted by the computer penalizes the student who selects a correct answer that is not included in the program. The task stimulus in such situations is inappropriate.

Two types of defective reinforcement contingencies have been observed during student use of computer software. First, the game or other exercise is often delayed because the keyboard is locked while stars twinkle, trains puff across the screen, or smiley faces wink or nod (Vargas, 1986, p. 75). A more serious problem occurs when the consequences that follow wrong answers are more interesting than the feedback for correct answers. In one computer exercise, for example, a little man jumps up and down and waves his arms after a wrong answer. Students, instead of solving the problems for the correct answers, randomly enter any answer in order to see the little man jump up and down (Gredler, 1992a).

Potential users of classroom computer games, therefore, should carefully review the exercises for several likely flaws. They are inappropriate vocabulary, too lengthy text, inadequate directions and branching, inadequate stimulus control, and defective reinforcement contingencies.

17.6.3 The Mixed—Metaphor Problem

Games are competitive exercises in which the objective is to win, and experiential simulations are interactive exercises in which participants take on roles with serious decision-making responsibilities. However, some developers have attempted to mix the two perspectives by assigning participants serious roles, placing them in direct competition with each other, and identifying the participants as winners or losers according to the individual's or team's performance. These exercises are sometimes referred to as *simulation games* and *gaming simulations*.

Games and experiential simulations, however, are different psychological realities, and mixing the two techniques is a contradiction in terms. Such exercises send conflicting messages to participants (Jones, 1984, 1987). They also can lead to bad feelings between participants who address their roles in a professional manner and those who treat the exercise as "only a game" (Jones, 1987).

Many exercises that otherwise would be classified as data management simulations are mixed-metaphor exercises. That is, student teams that each manage a "company" are placed in direct competition with each other with profitability as the criterion for winning. For example, in the Business Policy Game, the winning firm is the one with the highest return on investment. Further, in many classes, from 10% to 50% of the student's course grade depends on the team's performance.

Several problems recently have been identified with these exercises. Lundy (1985) observed that sometimes a

team that is not doing well in later rounds attempts to "crash the system." Seeing no way to win, team members behave like game players and behave in such a way as to prevent others from winning. Other desperation plays are charging an astronomical price for a product in hopes of selling a few, and end-of-activity plays, such as eliminating all research and development or ordering no raw materials (Teach, 1990). Some teams, however, view the exercise as simply a situation in which to show their prowess. Golden and Smith (1991) describe these teams as "dogfighters" because their behavior resembles that found in the classic World War II aviation dogfight.

The major problem with such exercises, however, is that competition in the business world does not routinely result in one company's being declared a winner while others enter bankruptcy (Teach, 1990). Instead, companies strive for market share and alter their strategies based on feedback about market conditions and the success of their earlier efforts. Thus, the focus on being "the winner" distorts the simulation experience.

Some researchers have investigated the factors that contribute to team success in these exercises. Gentry (1980) investigated the relationships between team size (three to five members) and various attitudinal and performance variables in three undergraduate business classes. However, of the variables entered into the stepwise regression equation to predict team standing, he found that group performance was predicted better by the ability of the best student in the group rather than by a composite of the group's abilities. Thus, group performance was more a function of a group leader rather than knowledge and ability of group members.

In addition, Remus (1977) and Remus and Jenner (1981) found a significant correlation between the student's enjoyment of the exercise and final standing of their teams. Several students in one study also disagreed with statements that the exercise was a valuable experience and represented real-world decision making (Remus & Jenner, 1981). In summary, the observations of Teach (1990), Golden and Smith (1991) and Lundy (1985), and the findings of Remus and Jenner (1981), lend support to the findings of Schild (1966). Specifically, students will tend to enact those behaviors that are reinforced by winning. In simulation games, these actions may be counterproductive to the expected learning.

17.6.4 Experiential Simulations

The student in an experiential simulation takes on a serious role in an evolving scenario and experiences the privileges and responsibilities of that role in attempting to solve a complex problem or realize a goal. Four major types of experiential simulations are data management, crisis management, and diagnostic and social-process exercises. Of these four types, crisis management simulations are developed to meet preestablished criteria regarding the nature of the crisis and expected student reactions. Data related to the development of these exercises typically are not reported for public consumption. Moreover, data management and social-process

simulations often (1) are not standardized exercises and/or (2) do not provide student data other than posttest achievement on some instructor-developed instrument.

Many diagnostic simulations, in contrast, are standardized situations in which optimal sequential decisions in relation to the evolving problem have been identified. Further, research conducted on the analyses of problem-solving decisions in diagnostic simulations can serve as a model for analyzing students' cognitive strategies in other types of simulations. The first step is the evaluation of the range of possible decisions at each decision point by a group of experts. Each decision is classified in one of five categories that range from "clearly contraindicated" to "clearly indicated and important," and a positive or negative weight (e.g., -1 to -3 or +1 to +3) is assigned to each decision (McGuire & Babbott, 1967, p. 5). Then, the combination of choices that represent a skilled decision-making strategy are summed for a total numerical score. When the simulation is administered, the numerical score of each student decision is recorded. The extent of congruence between the student's total and the expert decisions is referred to as a *proficiency score*.

A study of the problem-solving skills in simulations with 186 fourth-year medical students analyzed students' proficiency scores and revealed four different problem-solving styles (McGuire & Bashook, 1967). The high scorers included two groups identified as (1) thorough and discriminating and (2) the "shotgun" group. Although both groups earned total problem-solving scores between 32 and 60, the "shotgun" group made many choices that were not warranted (high errors of commission). Similarly, two problem-solving patterns were identified in the low-scoring group (scores below 30). One, the constricted group, chose few desirable or undesirable actions. In contrast, the other group, the random problem solvers, chose few desirable actions, but they also chose many actions that were not warranted.

This method of analyzing the specific characteristics of student performance in diagnostic simulations is applicable to other types of simulations that address problem-solving strategies. First, optimal strategies through the complex task or problem are identified. Other plausible steps are then weighted according to the extent to which they are neutral (do not advance the problem solution) or are debilitating. Finally, the number of debilitating decisions made by both high and low scorers is tabulated to identify the problem-solving pattern.

Given the recent emphasis on students' constructing knowledge during learning, this model or a similar one can provide information to teachers about specific student difficulties. Also, the computer can tabulate both total and component scores on students as they work through the exercise.

17.6.5 Symbolic Simulations

A symbolic simulation is a dynamic representation of a universe, system, process, or phenomenon by another system. The behavior that is simulated involves the interaction of at

least two variables over time. The student interacts with symbolic simulation from the outside, unlike the experiential simulation. The types of symbolic simulations are data universe, system, process, and laboratory-research simulations.

17.6.5.1. Data Universe Simulations. At present, few data universe simulations have been developed for instructional purposes. One example, however, is Jungck and Calley's (1985) Genetics Construction Kit (GCK). The software consists of two parts. One is a data universe that includes the complex behavior of 10 phenomena in classical Mendelian genetics. Operations that may be performed on this universe include crosses, comparisons of parental and filial generations, Chi-square analyses, and building up the number of progeny through successive experiments (Jungck & Calley, 1985). The second part develops "populations of organisms" for study that include combinations of the phenomena in the data universe (Stewart et al., 1992).

One study implemented GCK in the first 5 weeks of a 9-week high school genetics course. Students first completed an activity in which they built models to explain a "black-box" situation and then discussed the adequacy of their models for explaining the data. They worked in groups to research problems generated by GCK by building and testing models that appeared to explain the data (Stewart et al., 1992).

After 3 weeks, the researchers selected six students who had a good understanding of simple dominance and meiosis models. These students were presented individually with subsequent problems the others were studying in groups for 6 class days. Detailed analyses of their computer records and audio recordings of their "think-aloud" strategies indicated several findings. First, students revised their original explanatory models in most of the problems they encountered. Second, all but three of the final models were compatible with the data. Of these, half represented accepted scientific theory, and half represented an alternative perspective.

Third, and of primary importance to instructional design, the researchers documented a detailed and involved model-building process used by the students (see 12.3.1.1, 24.3.1). Among the actions initiated by the students were conducting experiments within the given field population, using an existing model to explain features of the data, using limitations of the proposed model to identify other possible causal factors, and bracketing cases of interest as a first step in revising the proposed model. Identification of the steps used by students in conducting research with other data universe simulations is a first step in developing instructional strategies for these simulations.

The variety of strategies that may be implemented by students when faced with a complex problem is illustrated by two different implementations of the genetics simulation CATLAB (Kinnear, 1982). The exercise permits students to construct a population of nonpedigree cats (up to 91 cats) and then to breed any two of the cats for any number of litters. In constructing the experimental population, the student chooses gender, tail or no tail, and color for each cat. If nonwhite is first chosen, then several options follow for both color and pattern. After the students complete their selec-

tions, the Apple II program provides rather stilted color images of the student's choices and the resulting litters.

One biology teacher reported that her students tended to breed cats without a plan (Vargas, 1986). The range of mixed characteristics in the resulting litters made it impossible for students to observe the relevant genetic principles. In addition, one student set about producing as many different-looking cats as possible. Vargas (1986, p. 742) concluded that the simulation *by itself* was no better than leaving a student unsupervised in a science laboratory to proceed by trial and error.

In contrast, Simmons and Lunetta (1993) implemented a three-part instructional strategy with three expert and eight novice problem solvers using CATLAB. The subjects were first directed to explore various traits with cats. In phase 2, the researcher had a brief discussion with each subject about his or her actions and rationale. Phase 3 required the subjects to investigate and determine the inheritance pattern of the orange and tabby striping trait.

The original intent of the study was to identify differences between expert and novice problem solvers in their interactions with the simulation. However, this dichotomy was too restrictive to explain the patterns of problem solving found in the data (Simmons & Lunetta, 1993). Instead, three levels of problem-solving performance were found. The highest level, successful problem solvers, consisted of two experts and two novices. This group (1) used systematic procedures, (2) developed valid reasons for their results, and (3) generated correct answers. They also had the highest percentage of correct responses (75%–100%). The second level, the transitional or less-successful problem solvers, consisted of one expert and three novices. Of their responses, 60% to 70% were correct. This group also used less-systematic procedures and generated some invalid explanations. In addition, they did not rule out alternative explanations that could account for their conclusions. The third level consisted of the unsuccessful problem solvers (five novices). These students exhibited the most random approaches to the problem and did not use valid scientific explanations. They typically used circular definitions to justify their actions (Simmons & Lunetta, 1993). From 35% to 45% of their responses were correct.

Analysis of the videotapes of the subjects indicated that successful problem solvers applied integrated knowledge during the process. Unsuccessful subjects, however, were unable to use domain-specific knowledge to describe their observations and were unable to detect the features of genetics concepts and principles in the data (Simmons & Lunetta, 1993). They also exhibited misunderstandings about the nature of probability. The findings of the study, which indicate three levels of problem solving, suggest that successful performance requires more than an advanced knowledge of the subject matter (Simmons & Lunetta, 1993). That is, both novices and experts exhibited a variety of strategies that ranged from least to most successful.

Data universe simulations lend themselves to several types of cognitive tasks. However, they are likely to be

unsuccessful unless students have developed a systematic strategy for approaching the task and also are able to apply an integrated knowledge base of concepts and principles.

17.6.5.2. System Simulations. Developers of complex equipment simulations typically establish performance standards for students and refine the simulation until those standards are met. Essential terms and definitions are typically taught prior to student engagement with the simulation.

Developing the skills of analysis and prediction in other system simulations with several variables presents a different instructional design problem. Students' prediction skills in relation to one system, water pollution, were investigated by Lavoie and Good (1988). In the system, five variables (temperature, waste type, dumping rate, type of treatment, and type of body water) affected oxygen and waste concentration of the water.

After a short period to explore the simulation, the 14 students read background material on water pollution that described some of the effects among the variables. They next worked through several exercises with the computer simulation which involved choosing preselected parameters and observing the effects on a given dependent variable. The students then were given three prediction problems to solve.

Problem-solving ability on the prediction problems was related to three factors: high or moderate initial knowledge, high academic achievement, and cognitive performance at the Piagetian stage of formal operational thinking. Unsuccessful students tended to have both low initial knowledge and low academic ability and to be at the Piagetian stage of concrete operational thinking.

One of the key differences between the Piagetian stages of concrete and formal reasoning is that concrete thinkers typically are able to manipulate systematically only one or two variables at a time. Given a more complex situation, they change several independent variables at a time and, therefore, cannot observe the effects of any one variable (Piaget, 1972; Gredler, 1992b). In contrast, formal operational thinkers are capable of developing hypotheses that systematically test the influence of several variables on an outcome. Analysis of the videotapes of the students confirmed that they executed the strategies consistently with their level of Piagetian reasoning.

In addition, the unsuccessful students expressed dissatisfaction and lack of interest at various times during the learning sequence (Lavoie & Good, 1988, p. 342). They also conducted, on average, 50% fewer simulation runs, took fewer notes than successful students, and spent less time reviewing and evaluating their predictions than the successful subjects. Further, a postexercise interview revealed that the unsuccessful students had more misconceptions about solubility and the relationships among oxygen, bacteria, and waste than the successful students.

The researchers also identified 21 behavioral tendencies that differed between successful and unsuccessful problem solvers. Others, in addition to those already mentioned, are that successful problem solvers made fewer errors in reading graphs, relied on information learned during the lesson

to make predictions, and understood the directions and information in the lesson. The implications for instructional design are clear. Systems in which several independent variables influence the values of two or more dependent variables are complex situations for students. Simulations of such systems should include preassessments of students' level of both Piagetian thinking and knowledge level. Students at the concrete level of thinking and/or with low subject knowledge should be directed to other materials prior to interacting with the simulation. Like the data universe simulations, a requisite skill is the capability of applying an integrated knowledge base to an unfamiliar situation.

17.6.5.3. Process Simulations. Often, naturally occurring phenomena are either unobservable or are not easily subject to experimentation. Examples include Newton's laws of motion, photosynthesis, and complex atomic reactions. Process simulations that can use symbols to represent the interactions of unobservable variables and which are subject to student manipulation can be useful instructional devices.

White (1984) designed and tested a series of exercises using symbols to confront students' misconceptions of Newton's laws of motion and conservation of momentum. A series of 10 exercises was designed that required students to conduct progressively more difficult operations on a spaceship in outer space (frictionless environment). Among the misconceptions addressed by the exercises is the intuitive belief that objects always go in the direction they are kicked (White, 1984).

Thirty-two students who had studied PSSC physics participated in the study. The 18 students in the experimental group and the 14 students in the control group did not differ significantly on the pretest problems. From 1/3 to 1/2 of the students demonstrated misconceptions about the effects in some of the basic questions. Posttest data indicated that the group that interacted with the simulation significantly improved their performance.

However, on the exercise involving prediction of the effects of an orthogonal impulse, the simulation exercise led to as many students changing from right pretest answers to wrong posttest answers as changed from wrong to right. Further, many of the exercises could be solved by simple heuristics, such as, "if one impulse (force or thrust) is not enough, try two" (White, 1984). The use of such strategies supports Kozma's (1992) concern that abstract symbols may not have a referent in another domain for the students (p. 206). That is, students may learn to operate directly on the objects without developing an understanding of the underlying principles.

Among the subsequent improvements to the exercise (White, 1994) are (1) additional structure, including "laws" to be tested in the simulation, (2) the addition of real-world transfer problems, and (3) the inclusion of other symbols to focus on important concepts. An example of an additional symbol is the use of a "wake" behind the spaceship to illustrate a change in velocity. Kozma (1992) reports that White (1994) found significant improvement on the transfer problems and significantly higher performance of students in a

2-month curriculum using the simulation than students in two regular physics classes.

A long-standing problem in education is the issue of overcoming students' misconceptions that are based on their limited everyday experience and intuitions. That is, students may be able to verbalize a phenomenon accurately, but when faced with a real-world problem, they revert to out-of-school knowledge as a basis for conceptualizing the situation (Alexander, 1992). Process simulations can be a powerful instructional tool to provide the repeated experiences that Piaget (1970) first identified as essential in overcoming these problems. However, careful attention to both symbol selection and links to laws and principles is required.

17.6.5.4. Laboratory Research Simulations. Laboratory research simulations consist of a series of discrete qualitative and quantitative experiments that students may direct in a specific subject area. Several studies have compared computer-based simulations with "wet labs" in chemistry and biology courses. The results, however, are confounded by one group or the other receiving extra materials, such as summary sheets, or written problems to solve following instructions.

One development, however, is a series of experiments for introductory college chemistry courses. The experiments were revised based on student comments during formative evaluation and then placed into a comparison group pilot study. The laboratory simulations use a single-screen system that permits computer text and graphics to be superimposed on video images. Components of the system are a personal computer, a video interface card, a videodisc player, and a television monitor. This system is more expensive than other configurations; however, an advantage is that students can respond to text questions while the images remain on the screen.

In the pilot study, 103 students were randomly assigned to a lab-only group, videodisc-only group, or videodisc-plus-lab group. Six interactive videodisc workstations were available on a self-scheduled basis for the students using the computer software. On a brief seven-point posttest, the difference between the means of the videodisc group and the laboratory group was 1.03 standard deviation units. Significant differences were also found between the means of the anonymously graded laboratory reports (videodisc-plus-lab = 31.04 and lab-only = 26.44). Also, students in the laboratory group were more likely to rely on the rote citation of examples in the lab manual even when these examples did not fit the data (Smith, Jones & Waugh, 1986).

17.6.6 Discussion

Research on games and simulations indicates three major areas that are essential for effective design: (1) the task-reinforcement structure, (2) the role of prior knowledge, and (3) the complexity of problem solving.

17.6.6.1. Task Reinforcement Structure. Both games and simulations alter the reinforcement structure of the

classroom because they expand the opportunities for students to earn reinforcement. Because winning is a powerful reinforcer, games must be carefully designed so that inappropriate strategies are not learned. Although teams-games-tournaments reinforces cooperation and peer tutoring, other games reinforce guessing and the selection of wrong answers.

The major task for game players is to win, whereas the task for simulation participants is to execute serious responsibilities identified by the nature of the simulation (experiential) or by the accompanying instruction (symbolic simulation). To mix games and simulations establishes conflicting tasks, i.e., defeating other participants or executing a role with identified responsibilities.

In contrast, experiential simulations establish particular tasks or goals for participants and provide contingencies in the form of changes in the complex problem or the actions of other participants. Designers of symbolic simulations, however, face particular problems. That is, simply providing a data universe, a system, or interacting processes is a necessary but not sufficient condition for a successful or meaningful problem-solving experience. For example, if the student's decisions result in a colorful screen display, the exercise reinforces random search strategies as well as thoughtful student choices.

Moreover, in the absence of prior instruction on conducting research in multivariate open-ended situations, some students will be unsuccessful. As indicated in one study, the unsuccessful students became frustrated and lost interest. Instead of a reinforcing exercise, the simulation becomes a form of punishment for the student's effort. One solution is to teach model-building strategies so that students become proficient in using them to solve broad open-ended problems. Another is to program the exercise such that random selection of variables initiates a message that suspends the simulation and routes the student to particular information sources for assistance, such as the teacher or particular instructional materials.

17.6.6.2. The Role of Prior Knowledge. Although the research on data universe, system, and process simulations is limited, the studies indicate the importance of prior knowledge on successful performance. Prior achievement level typically serves as an indicator of prior knowledge; however, this variable alone is insufficient to predict problem-solving performance. The research identifies two types of prior knowledge that appear to be essential in some simulations. One is domain-specific knowledge that must be integrated into a coherent whole. (Fragmented or partial knowledge is insufficient.) In one study, for example, unsuccessful students held several misconceptions about key topics.

A second type of knowledge essential for success is a systematic strategy for addressing a multifaceted situation. Students who had been taught to use models to explain data and to revise their models to account for new data were successful in conducting genetics research in a data universe simulation.

The capability of developing hypothetical models of a complex situation was found to be important in another

study. In a system simulation involving the interactions of several variables, formal Piagetian reasoning (as opposed to concrete reasoning) also was found to be essential. Of interest is that formal operational thinkers are capable of developing hypothetical models that are then tested systematically. In contrast, concrete operational thinkers can successfully manipulate only one or two variables at a time.

The implication for instructional design is that the identification of essential prerequisites, long an important design principle, involves at least two areas for some simulations. First, major concepts in the subject domain that are essential to manipulating variables or conducting research using the simulation should be identified. Level of academic achievement or a description of completed courses is insufficient to indicate essential prerequisite knowledge. In other words, variables identified in artificial-intelligence approaches to computer-based learning—i.e., problem-solving skill, aptitude, and ability (Tennyson & Park, 1987)—must be specified for the different types of simulations.

Second, the level of the task in terms of the number and nature of the variables to be manipulated also should be identified. Simulations that illustrate the interactive effects of several variables are more complex in terms of the reasoning strategies required for student success. Prior instruction in systematically manipulating variables may be required.

17.6.6.3. The Complexity of Problem Solving. Understanding problem solving in a variety of contexts is a major focus in cognitive theories of learning (Gredler, 1992b). Research on simulations suggests implications for these perspectives. One theoretical perspective, Gagné's conditions of learning, identifies five distinct categories of learning that differ in instructional requirements for successful learning. One of these domains is cognitive strategies, which consists of the skills essential to the student's management of his or her thinking and learning (Gagné, 1977, 1985). Cognitive strategies, however, may vary widely among students. Analyses of students' decisions in a diagnostic simulation, for example, indicated that successful students ranged from thorough and discriminating to the "shotgun" group, which chose many unwarranted actions. Analyses of students' strategies in a data universe simulation indicated 21 behavioral tendencies that differed between successful and unsuccessful problem solvers.

Another concern in terms of strategies acquired by the learner is that situational heuristics rather than generalizable principles may be learned. Thus, simulation design must incorporate links to the relevant theoretical framework.

Information-processing theories, another cognitive perspective, focus on the differences between expert and novice problem solvers. Research in several subject areas has identified general characteristics of both types of problem solvers (see Glaser & Chi, 1988). The expert/novice dichotomy, however, may oversimplify differences among individuals. One study, for example, found a continuum of capabilities from least to most successful that varied along the dimensions of (1) extent of integrated knowledge and (2) level of strategic reasoning.

A third cognitive development is that of constructivism (see Chapter 7). At present, no single constructivist theory of instruction has been developed (Driscoll, 1994). A basic tenet of constructivism, however, is that knowledge is a construction by the learner. That is, the learner interprets information in terms of his or her particular experience and constructs a knowledge base from these interpretations.

Beyond this common tenet, constructivism is interpreted by different proponents in somewhat different ways. Two of these views are particularly relevant for simulations. One view is based in part on Piaget's (1970) theory of cognitive development, which states that logical thinking develops from (1) the learner's confrontation with his or her misconceptions about the world and (2) the resulting reorganization of thinking on a more logical level. Thus, instruction should place learners in situations in which they must face the inconsistencies in their naive models of thinking. The process simulation discussed earlier that incorporates principles of Newtonian mechanics is an example.

Another perspective in constructivism is the view that authentic tasks with real-world relevance and utility should replace isolated decontextualized demands (Brown et al., 1989; Jonassen, 1991; Driscoll, 1994). Such tasks are particularly important in ill-structured domains such as medicine, history, and literature interpretation in which problems or cases require the flexible assembly of knowledge from a variety of sources (Spiro et al., 1991). Examples are diagnostic simulations in which students face complex, authentic, and evolving problems that they must attempt to understand and manage to a successful conclusion. Some data universe and system simulations, if accompanied by appropriate instruction, can also address the requirements of this constructivist view.

One concern that has been raised in relation to placing students in complex situations requiring many steps is that such tasks may overwhelm the less-capable learner (Dick, 1991, p. 42). In other words, the gap may be too great between the learner's capabilities and the tools and information provided in the exercise. The system simulation on water pollution is an example. The unsuccessful students lacked both basic knowledge related to the situation and systematic strategies for addressing multifactor problems, and expressed dissatisfaction and lack of interest several times during the activity.

In summary, the research on simulations indicates the varieties of cognitive strategies enacted by students in complex situations, and the range of differences between expert and novice problem solvers, and it offers a mechanism for empirically validating major concepts in constructivism.

17.7 RECOMMENDATIONS FOR FUTURE RESEARCH

Early research on games and simulations typically compared the particular interactive exercise with regular classroom instruction on information-oriented achievement tests.

These “apples and oranges” comparisons did not yield definitive information about the effectiveness of the innovations. Further, key processes in the innovation often were not documented, student characteristics that may interact with the exercise in different ways were not investigated, and outcome measures often were poorly described.

Conducting definitive research on games and simulations, however, requires more than the specification of additional variables and the description of student interactions and outcome measures. Specifically, if an exercise is poorly designed, documentation of implementation and outcomes contributes little to an understanding of the potential of the innovation (Gredler, 1996). A three-step strategy is essential to conducting useful research on games and simulations. The steps are: (1) Document the design validity of the innovation; (2) verify the cognitive strategy and/or social interaction processes executed by students during the exercise in small-group tryout (formative evaluation) and redesign where necessary; and (3) conduct follow-up research on specific processes and effects (see Chapters 39 to 42 for specific approaches to research).

17.7.1 Document Design Validity

Several issues important in design validity for both games and simulations are: (1) a reliance on a knowledge domain and subject-area expertise, (2) the exclusion of chance or random strategies as a means to success, and (3) the avoidance of mixed-metaphor exercises and zero-sum games.

Particularly important for simulations is the analysis of the mode of delivery and the causal model for events in the exercise. Specifically, social-process simulations cannot be delivered by the computer; however, any of the symbolic simulations are legitimate computer-based exercises.

The causal model for the simulation, whether quantitative or qualitative, should reflect verifiable processes and interrelationships, not random events. Some early computer-based exercises inadvertently established Russian-roulette situations for students in which the criteria for successful management are unknown to the participants. Students repeatedly assign values to a limited number of variables in the absence of a knowledge base and await the outcome. In such exercises, the students play against the odds established by the house (the computer program) instead of a real-world causal model (Gredler, 1992a).

Often, careful analysis is required to identify these variable-assignment exercises. An example is *Lemonade Stand*. First, students repeatedly assign values to only three variables. Thus, the same limited number of decisions is made again and again. The three variables are: (1) the number of glasses of lemonade one wishes to sell, (2) selling price per glass, and (3) amount of advertising expenditures. After students input their selections, the program compares them with the preprogrammed model and informs them of the amount of profit or loss for that day. Sometimes this figure is accompanied by the statement that the weather was

cloudy and rainy that day; thus, little or no profit was earned.

The inadequacy of the causal model also is noted by Vargas (1986). The exercise omits important considerations, such as the components of the lemonade (how much sugar and lemon to use in the brew), location of the stand, and the fact that few people would set up a stand in rainy weather. Thus, the exercise leads the prospective user to expect more than it delivers (p. 742). Further, the exercise is simply a guessing game for students as they attempt to discover the variable weightings that were selected by the programmer.

A much more useful exercise would be one that engages the students in planning for a lemonade stand in which weather data for past years as well as information on pedestrian traffic patterns, costs of resources, and so on are available. In this way, students' cognitive strategies may be facilitated.

17.7.2 Verification of Cognitive Strategy and/or Social Interaction Processes

A game or simulation that meets design criteria should then be implemented with a small group of students to determine the actual behaviors that it precipitates. This practice is a long-standing and accepted tenet of instructional design. However, many computer products marketed for schools do not undergo this test of effectiveness.

Important information can be obtained in tryouts of a game or simulation with answers to these questions: Do the students become frustrated and lose interest because the exercise is too difficult for them? Does success depend on skills other than those intended by the designers? What unanticipated behaviors do students execute during the exercise? What are learner attitudes toward the game or simulation?

Particularly important is the issue of task difficulty. A symbolic simulation that challenges the learner's naive conceptions or requires sophisticated research strategies beyond the learner's level of expertise is one that places high cognitive demand on the learner. Such a situation, in which the learner may be thrashing around with few resources for resolution, may generate reactions such as, “Why don't you just tell me what you want me to know?” (Perkins, 1991, p. 20).

Small-group tryout, in other words, is essential for determining whether intended processes and effects occur and the nature of unintended effects. Logistical difficulties in implementing the exercise also may be identified.

The researcher or designer then makes adjustments in the context for implementation, support materials for the exercise, or level of prerequisite knowledge and strategy use specified for the exercise, and implements the game or simulation with another small group. One alteration for a symbolic simulation, for example, may be to implement the exercise with a two-member team rather than as an individual exercise. In an experiential simulation, penalties for certain irresponsible actions may be added or the rules altered in order to deter unethical behavior.

17.7.3 Conduct Follow-up

Experiential exercises that meet design and formative evaluation criteria may then be further tested in group implementations. However, the type of research that is conducted on the exercise depends in part on the nature of the exercise and the purpose for which it was developed. Exercises that are designed to develop particular skills and capabilities traditionally provided by an existing instructional approach may be compared for effectiveness to that approach. For example, laboratory research simulations were developed for a viable option to the traditional "wet-lab" experience. In such a situation, comparisons of student performance between the computer-based and laboratory-based experiments on laboratory reports and posttests are logical. Also, system simulations that substitute learner operation of system components by computer-managed videodiscs may be compared to equipment-based instruction.

Similarly, business colleges often implement both data management simulations and case studies to provide students with experience in managing the finances of a company. Given similar goals, comparison research with these two types of exercises is legitimate. However, an important component of the research is to identify the types of student abilities, attitudes, and skills that interact with the exercises.

Other simulations, in contrast, typically address an instructional need that is not currently met by other forms of instruction. Diagnostic simulations, for example, were developed originally to bridge the gap between course work and hospital internships for medical students. Also, data universe and process simulations provide opportunities for students to conduct extended research and to confront their misconceptions and inadequate mental models. Such opportunities are not available in typical instructional situations.

For such simulations, a series of related exploratory studies is needed to determine the range and variety of reasoning and thinking strategies implemented by students and the effects. This research can make use of both quantitative and qualitative data. Pretests of domain knowledge and reasoning skills may be administered and then matched to the problem-solving strategies used by the students during the simulation and to other information to develop profiles of student interactions with these complex exercises.

Qualitative data in the form of analyses of students' problem-solving efforts may be obtained by (1) requesting students to verbalize their thoughts as they work through the exercise and by (2) videotaping the sessions. Transcriptions of the videotapes are then analyzed and coded to identify the specific steps implemented by each of the students. Semistructured individual interviews with students after their session(s) with the simulation can shed light on their noncognitive reactions to the experience.

Such research is time consuming and painstaking. However, strategy-based games and experiential and symbolic simulations offer opportunities for learning that are qualitatively different from those of direct instruction. The challenge is to develop the associated knowledge base for complex student-directed learning.

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