Science

Y Kali, Israel Institute of Technology, Haifa, Israel
M Linn, University of California, Berkeley, CA, USA

Most researchers would agree that science learners engage in a process of making sense of diverse information by looking for patterns and building on their own ideas (Bransford *et al.*, 1999; Bruer 1993). Linn *et al.* (2004) describe this process as knowledge integration and show that students benefit from curricula that elicit ideas and encourage linking and connecting information, seeking and evaluating new ideas, as well as revising and reorganizing scientific ideas to make them more comprehensive and cohesive. They note that designing curriculum materials to support and guide the process of knowledge integration has required creative innovations along with many cycles of trial and refinement. Recent progress in synthesizing design knowledge (Brown 1992; Bransford *et al.*, 1999) has generated principles and patterns that give new designers a head start on creating materials that promote knowledge integration.

In spite of extensive research showing that students learn using knowledge integration processes, textbooks, lectures, and even hands-on activities reflect a view of learners as absorbing information rather than attempting to integrate new ideas with their existing knowledge. Too often students learn isolated facts from science courses, form conjectures based on experience or observation, and gather information from peers or media, but do not sort these ideas out (e.g., Roseman *et al.*, 2001). Students frequently fail to connect ideas learned in science class with observations made in other contexts. Designing curriculum materials that promote knowledge integration requires consideration of the many ideas that students develop. Effective designs encourage learners to compare their ideas, formulate criteria for promoting one idea over another, and link ideas into arguments. However, the translation of what we know about how people learn into curriculum materials is not obvious. Our theoretical knowledge is too abstract to help curriculum designers make important decisions (Kali, 2006). Recent efforts in the area of science curriculum design seek to bridge this gap.

Described here are two complementary approaches for synthesizing science curriculum design knowledge: the design principles approach and the design patterns approach. Both trajectories view learning as a knowledge integration process and aim to synthesize design knowledge from a variety of research projects to make it useful for curriculum designers. We show how the two approaches complement each other by analyzing the design principles and design patterns in a thermodynamics curriculum unit. Then, we illustrate how the two approaches were used in a curriculum design and development course for graduate students. We also suggest ways in which they can be used in a curriculum design process. We conclude with a discussion of ways to make design knowledge useful.

Curriculum Development and Design-Based Research

Curriculum development is based on epistemological views of the designers. Designers have ideas about how learning takes place, such as a theory or a perspective on learning. They have epistemological assumptions about the nature of knowledge in a specific scientific domain. A good design process is sensitive to the needs and requirements of the users. A needs-analysis stage is therefore an important preliminary step in any curricular design process (Dick *et al.*, 2001). This stage is usually followed by a careful trial and refinement process, until the learning goals of the designed curriculum are met.

Design-based research is an emerging methodology for synthesizing the lessons learned from this trial and refinement process. To draw conclusions from these studies, researchers contrast multiple versions (Barab and Squire, 2004; Collins *et al.*, 2004; The Design-Based Research Collective, 2003). Design-based research studies contribute to what we know about how people learn. They also widen the body of design knowledge available for future curriculum development. To make this body of knowledge, which is sometimes referred to as design knowledge, become useful for curriculum designers, researchers have sought to abstract general guidelines that are based on large numbers of studies, and can assist curriculum designers to make important decisions (e.g., Brown, 1992; Quintana *et al.*, 2004; Merrill, 2002; Mor and Winters, 2007; van den Akker, 1999).

Design Principles and Design Patterns: Complementary Approaches

Researchers have begun to develop two approaches, which use different lenses to analyze promising curricular innovations, find common productive design elements, tie

them with theory, and articulate them as guidelines for future curriculum designers. Described below are two approaches which show how they can be used together in a curriculum design process.

The design principles approach

The design principles approach uses design principles as an organizational unit for synthesizing design knowledge (Merrill, 2002; Quintana *et al.*, 2004). Bell and co-workers describe design principles as:

> ...an intermediate step between scientific findings, which must be generalized and replicable, and local experiences or examples that come up in practice. Because of the need to interpret design principles, they are not as readily falsifiable as scientific laws. The principles are generated inductively from prior examples of success and are subject to refinement over time as others try to adapt them to their own experiences. (Bell *et al.*, 2004: 83)

Based on this approach, the Design Principles Database (Kali and Linn, 2008) was developed. This database is a mechanism to support researchers and curriculum designers to share their design knowledge in the form of design principles, exemplified by descriptions of features from learning environments. The database is an infrastructure for participants to publish, connect, discuss, and review design ideas, as well as to use these ideas to design new curricula. Thus, it serves as a collaborative knowledge-building tool as well as a mechanism to support design-based research (Kali, 2006). The current entries in the Design Principles Database represent the contributions of over 60 individual researchers. The database includes more than 100 features (mainly from physical, life, and earth sciences), connected with several dozen design principles.

For example, one feature in the database is labeled "Multiple representations in WorldWatcher". This feature of WorldWatcher software provides scientific visualizations for the investigation of weather data. Students can explore weather data using visualizations that are similar to those found in environments that scientists use (Edelson *et al.*, 1999). The feature displays two-dimensional global data in the form of color maps with latitude and longitude markings and an optional continent outline overlay. A constantly updated readout follows the user's mouse as it travels over an image, displaying the latitude, longitude, country or state/province, and temperature data value. Different types of representations of the data (such as textual representations of temperature, color schemes representing temperature, location of a mouse on the continent outline, and textual representations of the location as latitude and longitude) are linked, and changed synchronously as the mouse moves.

The feature "Multiple representations in WorldWatcher" is linked in the database to a design principle named "Use multiple-linked representations". This principle connects to about ten other features in the database. It provides a general rationale, theoretical underpinning, and important considerations, such as pitfalls, trade-offs, and limits of practical use, to help designers benefit from the many examples. This principle is applied in the thermodynamics curriculum unit described below.

The design patterns approach

The second approach for synthesizing design knowledge to support curriculum designers is the design patterns approach. A design pattern is a sequence of activities in a curriculum, followed by teachers and students in a classroom (Linn and Eylon, 2006). Design patterns based on knowledge integration involve four basic processes: (1) eliciting student ideas, (2) adding new, pivotal ideas, (3) developing criteria for distinguishing among ideas, and (4) sorting out ideas. Linn and Eylon (2006) illustrate how these four processes play out in ten design patterns, which research has shown, can promote knowledge integration (right column in **Table 1**).

For example, one of the ten patterns is "Experiment". This pattern captures successful sequences of activities that support students in learning from experiments. It describes a recursive process of defining and refining an inquiry question, generating methods for investigating the question, carrying out the investigation, evaluating the results, and using the findings to sort out students' own repertoire of ideas. When students use activities designed with the experiment pattern, they make decisions about what is a good experiment and what can be learned from an experiment. Students learn to select among varied data collection procedures, distinguish causal from correlational results, and link methods of investigation to the validity of findings (Linn and Eylon, 2006). The experiment pattern can help designers find ways to take advantage of hands-on learning.

This pattern appears in a curricular sequence of activities in the Learning by Design project (Kolodner *et al.*, 2003). Activities in this project interweave design and experimentation cycles. In the experimentation cycle, students begin by clarifying the question to be addressed and make a hypothesis. Then, they design the investigation by identifying conditions that need to be controlled, the variables that will be varied and their values, the steps to be carried out, the number of trials, and what to measure. Finally, students carry out the investigation, record data, analyze results, and present their findings in a poster session (Kolodner *et al.*, 2003).

To illustrate how the design principles and the design patterns approaches complement each other, in the following section we analyze a specific curricular unit in thermodynamics, using these two lenses. The juxtaposition of the two lenses highlights the different ways in which each of the approaches guides design of science curricula.

Table 1   Intuitions in sequences designed by students (left column) and design patterns that provide alternatives (right column)

Intuitions in sequences designed by graduate students in the Kali and Ronen-Fuhrmann (2007) research	Design pattern providing an alternative along with relevant guidance
Focus on flow of content rather than student engagement. Students' sequences focused on which content should be learned first and how to communicate a hierarchy of knowledge. They did not think enough about how to engage learners.	Pattern: *orient and elicit*. Instructors use the orient-and-elicit pattern to increase interest in a scientific phenomena, define the scope of the topic, connect the topic to personally relevant problems, link the new topic to prior instruction, gauge student interest, and identify the learner's entering ideas.
Providing instructions rather than diagnosing possible confusions. Students tended to start their sequences with instructions, instead of designing guidance that diagnoses learners' possible confusions, or enables learners to link to specific instructions when and if these are needed.	Pattern: *diagnose and guide*. Instructors use the diagnose-and-guide pattern to elicit the learner's ideas, identify confusions, and determine which ideas to add to stimulate knowledge integration. This pattern promotes knowledge integration by motivating instructors to analyze student thinking and select the more effective new idea.
Providing information rather than supporting inquiry. Students tended to provide information rather than support inquiry; providing learners with answers was often supported by visualizations, but these were usually designed to inform, rather than enable learner-exploration of phenomena.	Pattern: *predict, observe, explain*. The predict, observe, explain pattern involves providing a demonstration of a scientific phenomenon, eliciting predictions, running the demonstrations, and asking the learner to reconcile contradictions.
	Pattern: *explore a simulation*. The explore-a-simulation pattern enables learners to try out their ideas using simulations, virtual worlds, or scientific models. Simulations elicit ideas, support the testing of ideas with feedback, and encourage learners to monitor their performance, often in relationship to their peers or an ideal performer.
Seeking expected answers rather than encouraging negotiation of ideas. Students sought to provide a typical correct answer, or process, rather than illustrate a variety of ideas, and encourage negotiation of those ideas among peers.	Pattern: *illustrate ideas*. Using the diagnose-and-guide pattern described above, instructors illustrate their ideas by contrasting various perspectives – including those held by their audience – and discussing how a learner could go about distinguishing among them.
	Pattern: *collaborate*. In this pattern learners generate their own ideas, learn from the ideas of others, respond to group ideas, determine methods for distinguishing ideas, articulate warrants for their views, and reach consensus.
	Pattern: *critique*. In this pattern learners are asked to evaluate both established and potentially invalid, misleading, persuasive, or confusing information presented in Internet resources, textbooks, articles, models, experiments, arguments, or peer reports.
	Pattern: *reflect*. In this pattern learners are encouraged to analyze the connections they make and consider their prior ideas. The reflect pattern promotes knowledge integration by encouraging students to stop and analyze their own repertoire of ideas.
Recreations rather than enabling learners to design their own artifacts. Students tended to engage learners in predefined activities and rarely enabled learners to design their own artifacts	Pattern: *create an artifact*. The create-an-artifact pattern involves refining a question, selecting or using methods for creating an artifact, creating a draft artifact, evaluating the results, using the findings to improve the artifact, and connecting the results to views of the topic.

Design Principles and Patterns in the Thermodynamics Curriculum Unit

"Thermodynamics: probing your surroundings" (Clark and Sampson, 2007) is a curriculum unit for seventh- to ninth-grade students, which is part of the Technology-Enhanced Learning in Science program. The unit, which requires about 1 week of instruction, and uses the Web-based Inquiry Science (WISE) infrastructure, is designed to assist students to connect their observations (such as noting that metal feels cooler than wood at room temperature), and the explanations of these phenomena at the molecular level.

The design of this unit can be analyzed using design principles as well as design patterns. This dual analysis is described below and summarized in **Figure 1** (see below). The design principles and patterns are concisely summarized here. Information about each of the principles can be found in the Design Principles Database. The design patterns are explained in more detail in Linn and Eylon (2006).

The first activity in the unit, named "What do you think?" (**Figure 1**), introduces a driving question and elicits students' ideas about thermodynamics. (People talk about objects being naturally hot or naturally cold – what do they mean?) Students make predictions about the
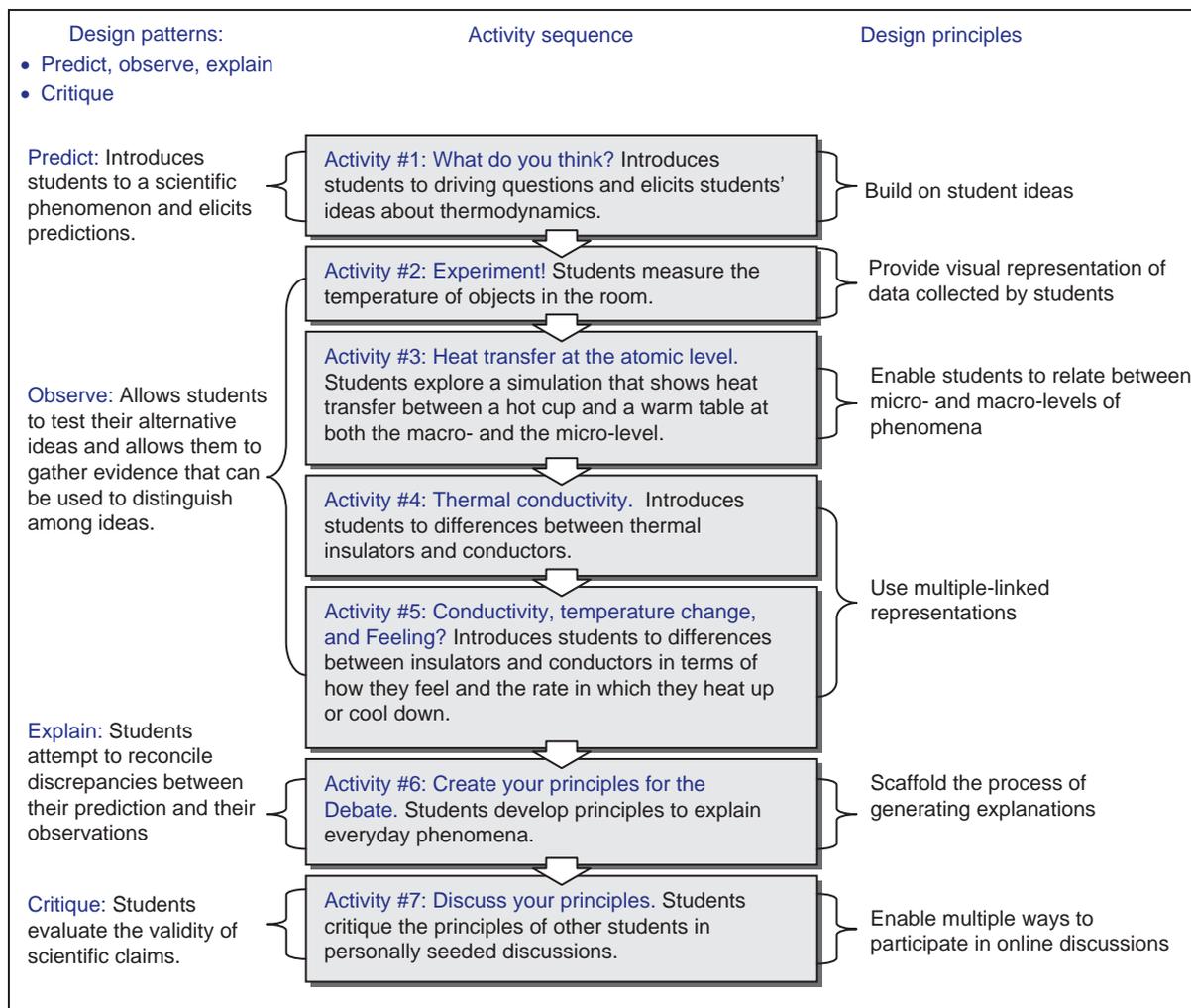
Figure 1 The sequence of activities in the thermodynamics curriculum unit described in terms of design patterns (left) and design principles (right). From Clark, D. B. and Sampson, V. D. (2007). Personally-seeded discussions to scaffold online argumentation. International Journal of Science Education 29, 253–277.

temperature of various objects in the room, and record them online. If we analyze this feature with a design principles lens, we can see that it employs a most prominent principle for designing scientific curricula called "Build on student ideas". This design principle calls for designing instruction that encourages students to build on their ideas to develop increasingly powerful and useful scientific ideas, rather than isolate new information from existing knowledge. This first activity (**Figure 1**) also illustrates the design patterns approach. The activity realizes the predict part of a design pattern named "Predict observe explain" (**Table 1**). The other segments (observe and explain) follow in activities as the unit progresses.

In the second activity of this unit, students measure the temperature of the objects and compare the measurements to their predictions using a feature that graphically presents predicted versus actual temperatures. From a design principles view, this feature follows the principle "Provide visual representation of data collected by

students". The tool enables students to easily represent data they collect (temperature, time, and data from surveys) in interactive dynamic representations. Graphing data collected by students can promote their understanding of the phenomenon they are studying. Using tools that automatically graph data collected by students decreases the workload involved in graphing. From a design patterns view, this one, and the next three activities represent the observe section of the "Predict observe explain" pattern described above (**Figure 1**; **Table 1**).

Students' exploration continues in the third activity with a simulation that shows heat transfer between a hot cup and a warm table at both the observable and molecular level. The simulation applies the design principle "Enable students to relate macro- and micro-levels of phenomena". This principle calls for creating features that help students see the connection between their observations and molecular processes by animation that allows students to zoom into the phenomena until molecules

can be seen. Then, in the fourth and fifth activities, students learn about the differences between thermal insulators and conductors. They choose different objects with various conductivities and different starting temperatures for each object, and view animated graphs showing how their temperature changes as they heat up or cool down. This animation realizes the design principle described above – "Use multiple-linked representations".

The sixth and seventh activities, which culminate the thermodynamics unit, enable students to develop their own principles for explaining everyday phenomena in terms of concepts in thermodynamics, and to discuss these principles with their peers. Using a tool called "Principle maker", students create general principles that summarize their understanding of simulations and of data collected in previous stages of the project. The students use a series of pull-down menus in order to construct a principle. Each pull-down menu gives a list of possible phrases to choose from. Finally, the principles created in activity 6 are used as seeds for online discussions between students in activity 7.

Activities 6 and 7 represent curriculum features that employ two design principles: "Scaffold the process of generating explanations" and "Enable multiple ways to participate in online discussions". From a design patterns view, when students use the "Principle maker", they accomplish the explain section of the "Predict observe explain" pattern, followed throughout the sequence of activities 1–6. The online discussion, seeded with students' principles in the final activity, represents a new pattern – the "Critique" pattern, which guides designers to create sequences of activities that support students in careful examination of any information they encounter, including ideas brought to the discussion by their peers (**Table 1**).

The above analysis is only one example of ways in which a curriculum unit can be analyzed using design principles and design patterns. Curricular features and sequences can realize more than one design principle or design pattern. Principles and patterns can be embedded into one another. For instance, activity 3 in the thermodynamics unit is part of the "Predict observe explain" sequence and also implements the "Explore a simulation" pattern as part of the observation. This pattern enables designers to create sequences of activities that specifically support students in making sense of new science ideas represented in scientific models and simulations (**Table 1**).

Using Principles and Patterns to Guide a Curriculum Design Process

Researchers are beginning to tap the potential use of frameworks, such as the design principles and design patterns described above to improve the design process. Research highlights the affordances and challenges they pose for designers. To assess the use of the design principles approach, Kali and Ronen-Fuhrmann (2007) developed a course to guide graduate students in designing technology-based curricula using the Design Principles Database. Students use the database when they: (1) write a needs and analysis document for the curriculum they are designing, (2) brainstorm ideas for features, (3) create a flow of activities, (4) design the features in the activity flow, and (5) evaluate each others' designs.

Initial enactments of this model in graduate courses showed that design principles were useful to students in several of these stages. For instance, the use of design principles at the brainstorming stage helped students to widen the scope of their design. Students were more likely to include socioconstructivist features than before they used the principles. Additionally, after students figured out a sequence of activities for the curricula, the Design Principles Database helped them design innovative features for each activity in the sequence and, thus, build on ideas tested and refined by other design-based research studies. However, designing the sequence of activities was a challenge for many of the students. They tended to rely on their intuitive absorption model of the learner and: (1) create a hierarchical flow of content rather than engaging students, (2) provide instructions rather than diagnose possible confusion, (3) provide information rather than support explanation, (4) seek predefined answers rather than encourage negotiation, and (5) create actions rather than enabling learners to design artifacts (Kali and Ronen-Fuhrmann, 2007; **Table 1**).

To remedy this problem, the next version of the course will employ design patterns. **Table 1** illustrates how the patterns approach could help graduate students, in the Kali and Ronen-Fuhrmann (2007) study, consider alternative approaches and analyze their intuitive designs from another perspective.

The above analysis shows the benefit of using design patterns in the create-a-flow-of-activities stage of the design process. Recently, the design patterns have been added to the publicly accessible Design Principles Database, so that novice curriculum designers will be able to use design principles as well as design patterns throughout their design process.

Summary and Next Steps

Current curriculum materials, including textbooks (Roseman *et al.*, 2001) and lectures (Linn and Eylon, 2006), fail to take advantage of advances in understanding of the learner and of effective instruction. Since the 1990s, researchers have sought learning principles (Brown, 1992)

and design knowledge (diSessa, 1992) to remedy this situation. With the advent of technology-enhanced learning environments, many research partnerships have used embedded assessments to gather detailed accounts of student learning of complex science concepts (e.g., Clark and Sampson, 2007; Kolodner *et al.*, 2003). These research programs feature trial and refinement of curricular materials using evidence from student learning (The Design-Based Research Collective, 2003). Efforts to synthesize which refinements succeed have typically involved generating design principles (Collins *et al.*, 2004; Dick *et al.*, 2001; Linn *et al.*, 2004; van den Akker, 1999) or design patterns (Linn and Eylon, 2006).

Recently, researchers have begun to study ways to synthesize design knowledge so others can use it. Kali (2006) created the public Design Principles Database and engaged the community in contributing its design knowledge. Kali and Ronen-Fuhrmann (2007) created a curricular design course for graduate students and studied the role of principles in the design process. Based on analyses of student designs, they found that principles were not sufficient to help students take advantage of research on instruction. The most recent version of the course and the Design Principles Database now also includes design patterns. These first steps toward creating effective, proven designs suggest promising practices for all designers. Future research must apply this rigorous, evidence-based approach to the design of widely used materials, such as textbooks.

Acknowledgment

Bibliography

Barab, S. A. and Squire, K. D. (2004). Design-based research: Putting our stake in the ground. *The Journal of the Learning Sciences* **13**, 1–14.

Bransford, J. D., Brown, A. L., and Cocking, R. R. (eds.) (1999). *How People Learn: Brain, Mind, Experience, and School.* Washington, DC: National Research Council.

Bell, P., Hoadley, C. M., and Linn, M. C. (2004). Design-based research in education. In Linn, M. C., Davis, E. A., and Bell, P. (eds.) *Internet Environments for Science Education*, pp 73–85. Mahwah, NJ: Lawrence Erlbaum Associates.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *Journal of the Learning Sciences* **2**, 141–178.

Bruer, J. T. (1993). *Schools for Thought: A Science of Learning in the Classroom*. Cambridge, MA: MIT Press.

Clark, D. B. and Sampson, V. D. (2007). Personally-seeded discussions to scaffold online argumentation. *International Journal of Science Education* **29**, 253–277.

Collins, A., Joseph, D., and Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *Journal of the Learning Sciences* **13**, 15–42.

Dick, W., Carey, L., and Carey, J. O. (2001). *The Systematic Design of Instruction* (5th edn.), pp 1–34. New York: Longman.

diSessa, A. (1992). Images of learning. In De Corte, E., Linn, M. C., Mandl, H., and Verschaffel, L. (eds.) *Computer-Based Learning Environments and Problem Solving.* Berlin: Springer.

Edelson, D., Gordin, D., and Pea, R. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences* **8**, 391–450.

Kali, Y. (2006). Collaborative knowledge-building using the design principles database. *International Journal of Computer Support for Collaborative Learning* **1**, 187–201.

Kali, Y. and Linn, M. C. (2007). Technology-enhanced support strategies for inquiry learning. In Spector, J. M., Merrill, M. D., van Merriënboer, J. J. G. V., and Driscoll, M. P. (eds.) *Handbook of Research on Educational Communications and Technology,* 3rd edn., pp 445–490. Mahwah, NJ: Erlbaum.

Kali, Y. and Ronen-Fuhrmann, T. (2007). How can the design of educational technologies affect graduate students' epistemologies about learning? In Chinn, C. A., Erkens, G., and Puntambekar, S. (eds.) *Proceedings of the Computers Supported Collaborative Learning (CSCL)*, Mice, Minds and Society, pp 320–322. International Society of the Learning Sciences, Inc.

Kolodner, J. L., Camp, P. J., Crismond, D., *et al.* (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting Learning by Design™ into practice. *Journal of the Learning Sciences* **12**, 495–547.

Linn, M. C., Davis, E. A., and Bell, P. (eds.) (2004). *Internet Environments for Science Education.* Mahwah, NJ: Lawrence Erlbaum Associates.

Linn, M. C. and Eylon, B.-S. (2006). Science education: Integrating views of learning and instruction. In Alexander, P. A. and Winne, P. H. (eds.) *Handbook of Educational Psychology,* 2nd edn., pp 511–544. Mahwah, NJ: Lawrence Erlbaum Associates.

Merrill, M. D. (2002). First principles of instruction. *Educational Technology Research and Development* **50**, 43–59.

Mor, Y. and Winters, N. (2007). Design approaches in technology enhanced learning. *Interactive Learning Environments* **15**, 61–75.

Quintana, C., Reiser, B. J., Davis, *et al.* (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences* **13**, 337–386.

Roseman, J. E., Kulm, G., and Shuttleworth, S. (2001). Putting textbooks to the test. *ENC Focus* **8**, 56–59.

The Design-Based Research Collective (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher* **32**, 5–8.

van den Akker, J. (1999). Principles and methods of development research. In van den Akker, J., Nieveen, N., Branch, R. M., Gustafson, K. L., and Plomp, T. (eds.) *Design Methodology and Developmental Research in Education and Training*, pp 1–14. The Netherlands: Kluwer Academic.

Further Reading

Alexander, C., Ishikawa, S., and Silverstein, M. (1977). *A Pattern Language: Towns, Buildings, and Construction*. New York: Oxford University Press.

Collins, A. (1992). Toward a design science of education. In Scanlon, E. and O'Shea, T. (eds.) *New Directions in Educational Technology*, pp 15–22. Berlin: Springer.

diSessa, A. A. (2000). *Changing Minds: Computers, Learning and Literacy*. Cambridge, MA: MIT Press.

Simon, H. A. (1969). *The Sciences of the Artificial*. Cambridge, MA: MIT Press.

Relevant Websites

http://www.design-principles.org – Design principles database.
http://www-static.cc.gatech.edu – Learning by Design.

http://telscenter.org – Technology-Enhanced Learning in Science (TELS).
http://wise.berkeley.edu – Web-based inquiry science environment (WISE).
http://www.worldwatcher.northwestern.edu – World watcher.