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AUTHOR/S: Kali, Y, and Linn, M.

AUTHOR CONTACT DETAILS

Yael Kali  
The Technion – Israel Institute of Technology  
The Department of Education in Technology and  
Science  
Haifa 32000,  
Israel  
[yaelk@tx.technion.ac.il](mailto:yaelk@tx.technion.ac.il)

Marcia Linn  
University of California, Berkeley  
4611 Tolman Hall, mc1670  
Berkeley, CA 94720,  
USA  
[mclinn@berkeley.edu](mailto:mclinn@berkeley.edu)

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## **CURRICULUM DESIGN – AS SUBJECT MATTER: SCIENCE**

### Abstract

Research during the past decade has greatly enriched our knowledge about ways that curriculum design can impact learning in science. An important contribution comes from design-based research – an emerging methodology. Researchers have sought to synthesize refinement studies of curricular innovations. Frameworks to organize design knowledge are emerging. We demonstrate the potential use of such frameworks to guide the process of curricular design by describing two approaches for synthesizing design knowledge: the Design Principles, and the Design Patterns approaches. Both approaches view science learning as a process of knowledge integration. These approaches can contribute to courses in curriculum design and help designers build on widely used materials to improve student learning.

### Keywords

10-15 keywords, which will be used for indexing purposes only. These should be listed alphabetically

Assessment  
Curriculum  
Design patterns  
Design principles  
Design Principles Database  
Knowledge Integration  
Scaffolding  
Science Education  
Technology Enhanced Learning in Science (TELS)  
Web-based Inquiry Science Environment (WISE)

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## Introduction

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, Brown and Cocking 1999, Bruer 1993). Linn, Davis and Bell (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 plus many cycles of trial and refinement. Recent progress in synthesizing design knowledge (Brown 1992, Bransford, Brown and Cocking 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 (for example, Roseman, Kulm and Shuttleworth 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, to formulate criteria for promoting one idea over another, and to 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. We illustrate how the two approaches were used in a curriculum design and development course for graduate students. We 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 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, Carey and Carey 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, Joseph and Bielaczyc 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 (for example, 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, Hoadley, and Linn (2004) 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.” (p. 83).

Based on this approach, the Design Principles Database (Kali and Linn, in press) was developed. The 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 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 sixty individual researchers. The database includes about one hundred 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, Gordin and Pea 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. The principle provides a general rationale, theoretical underpinning, and important considerations, such as pitfalls, tradeoffs 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: a) eliciting student ideas, b) adding new, pivotal ideas, c) developing criteria for distinguishing among ideas, and d) sorting out ideas. Linn and Eylon (2006) illustrate how these four processes play out in ten design patterns that research has shown can promote knowledge integration (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. The pattern 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, steps to be carried out, the number of trials, 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.

### Design principles and patterns in the thermodynamics curriculum unit

“Thermodynamics: Probing Your Surroundings” (Clark and Sampson 2007) is a curriculum unit for 7<sup>th</sup> to 9<sup>th</sup> grade students, which is part of the Technology Enhanced Learning in Science program. The unit, which requires about one week of instruction, and uses the WISE (Web-based Inquiry Science) 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 student ideas about thermodynamics. (People talk about objects being “naturally hot” or “naturally cold” - What do they mean?). Students make predictions about the 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 more and more 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 vs. 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, 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 work load involved in graphing. From a design patterns view, this, 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).

< Insert Figure 1 about here >

### 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: a) write a needs and analysis document for the curriculum they are designing, b) brainstorm ideas for features, c) create a flow of activities, d) design the features in the activity flow, and e) 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 socio-constructivist 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: a) create a hierarchical flow of content rather than engaging students, b) provide instructions rather than diagnose possible confusion, c) provide information rather than support explanation, d) seek pre-defined answers rather than encourage negotiation, and e) 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.

< Insert Table 1 about here >

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, Kulm & Shattleworth 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 (for example 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, Joseph and Bielaczyc, 2004, Dick, Carey and Carey, 2001; Linn, Davis and Bell, 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 their 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 towards 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.

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### Further reading

Further Reading list for books, chapters, reviews or seminal articles to which the reader can be directed for further information on the topic.

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### Cross references

Suggestions for cross-references to other articles within the work

### Websites

- Design Principles Database <http://www.design-principles.org>
- Technology Enhanced Learning in Science (TELS) <http://telscenter.org/>
- Web-based Inquiry Science Environment (WISE) <http://wise.berkeley.edu/>
- World Watcher <http://www.worldwatcher.northwestern.edu/>
- Learning by Design <http://www-static.cc.gatech.edu/projects/lbd/>

## Author Biography

**Yael Kali** is a faculty member at the Education in the Science and Technology Department at the Technion in Israel. The group she is leading at the Technion focuses on design-principles for educational technologies, and studies how technology enhanced learning environments affect student learning at different age levels (middle-school to higher-education). She is a co-principle investigator in the NSF-funded Technology Enhanced Learning in Science (TELS) center, in which she develops the Design Principles Database, and studies its contribution to the Learning Sciences and Design communities. She is the director of the NSF-funded Delineating and Evaluating Coherent Instructional Designs for Education (DECIDE) project - a collaboration between two Centers for Learning and Teaching (CLTs): TELS Center, and the Center for Curriculum Materials in Science (CCMS), aimed at to synthesize ideas about how to design instruction that leads to coherent understanding of science.

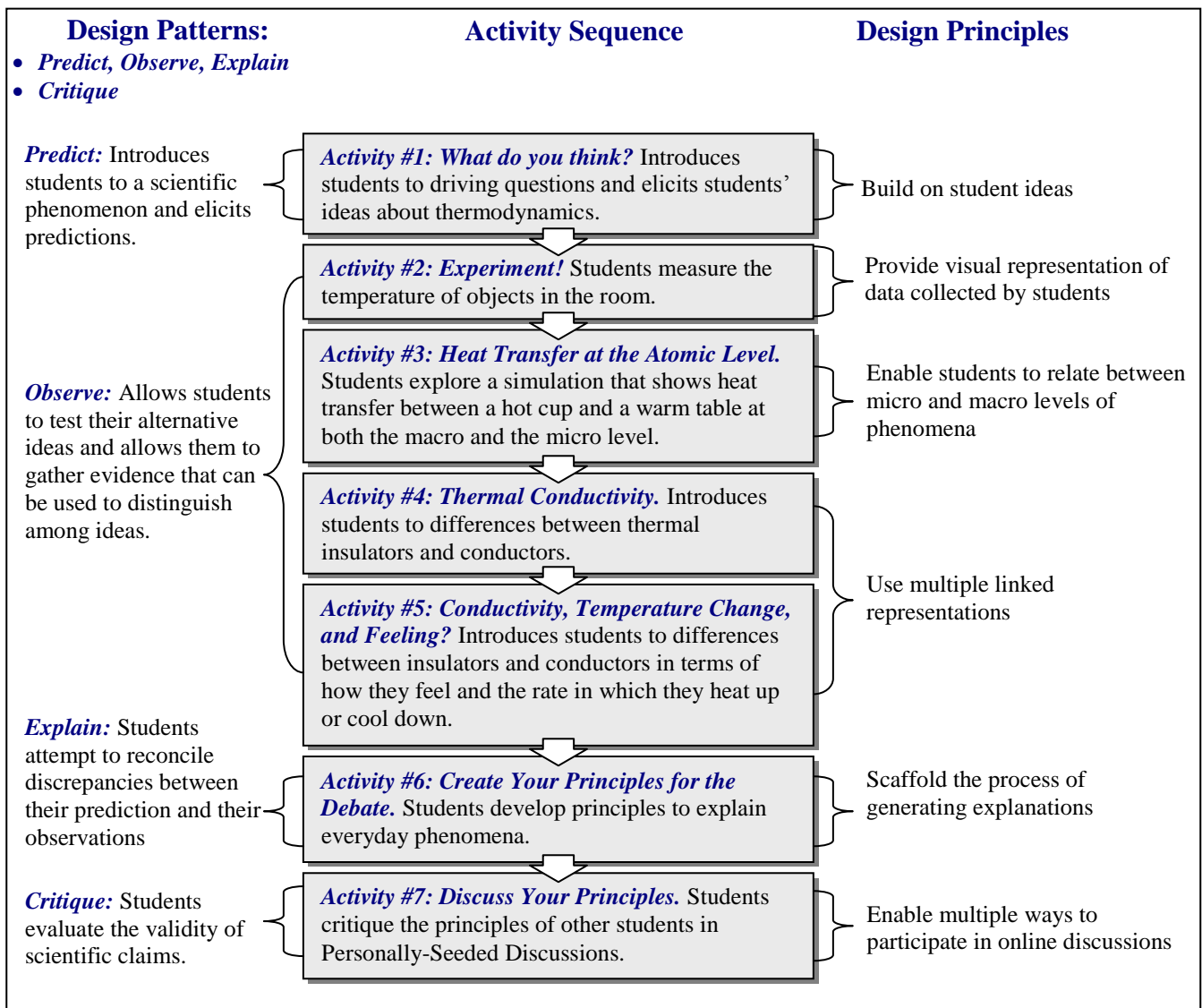


**Marcia C. Linn** is professor of development and cognition specializing in education in mathematics, science, and technology in the Graduate School of Education at the University of California, Berkeley. She directs the NSF-funded Technology-enhanced Learning in Science (TELS) center. Board service includes the American Association for the Advancement of Science board, the Graduate Record Examination Board of the Educational Testing Service, the McDonnell Foundation Cognitive Studies in Education Practice board, and the Education and Human Resources Directorate at the National Science Foundation. She is a member of the National Academy of Education. She is a Fellow of the American Association for the Advancement of Science, the American Psychological Association, and the Center for Advanced Study in Behavioral Sciences. Her books include *Computers, Teachers, Peers* (2000), and *Internet Environments for Science Education* (2004). Awards include the National

Association for Research in Science Teaching Award for Lifelong Distinguished Contributions to Science Education and the Council of Scientific Society Presidents first award for Excellence in Educational Research.



## FIGURES AND TABLES



**Figure 1:** The sequence of activities in the thermodynamics curriculum unit described in terms of design patterns (left) and design principles (right). Revised from Clark and Sampson (2007).

<i>Intuitions in sequences designed by graduate students in the Kali and Ronen-Fuhrmann (2007) research</i>	<i>Design pattern providing an alternative along with relevant guidance</i>
<p><b>Focus on flow of content rather than student engagement.</b> Students' sequences focused on which content should be learned first and how to communicate a hierarchy of knowledge. They didn't think enough about how to engage learners.</p>	<p><b>Pattern: Orient and Elicit.</b> 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.</p>
<p><b>Providing instructions rather than diagnosing possible confusions.</b> 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.</p>	<p><b>Pattern: Diagnose and guide.</b> 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.</p>
<p><b>Providing information rather than supporting inquiry.</b> 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.</p>	<p><b>Pattern: predict, observe, explain.</b> 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.</p> <p><b>Pattern: explore a simulation.</b> 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.</p>
<p><b>Seeking expected answers rather than encouraging negotiation of ideas.</b> 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.</p>	<p><b>Pattern: Illustrate ideas.</b> 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.</p> <p><b>Pattern: Collaborate.</b> 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.</p> <p><b>Pattern: Critique.</b> In this pattern learners are asks to evaluate both established and potentially invalid, misleading, persuasive, or confusing information presented in Internet resources, textbooks, articles, models, experiments, arguments, or peer reports.</p> <p><b>Pattern: Reflect.</b> 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.</p>
<p><b>Recreations rather than enabling learners to design their own artifacts.</b> Students tended to engage learners in predefined activities and rarely enabled learners to design their own artifacts</p>	<p><b>Pattern: create an artifact.</b> 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.</p>

**Table 1:** Intuitions in sequences designed by students and design patterns that provide alternatives