Chapter 4

Inquiry Learning: What Is It? How Do You Do It?

by Laura Trout, Chris Lee, Rick Moog, and Dawn Rickey

Laura Trout *has a B.S. in chemistry from Central Washington University and an M.S. in chemistry from the University of Washington. She has taught high school chemistry for 14 years, currently teaching chemistry I at Lancaster Country Day School in Lancaster, PA. Laura has used and written Process-Oriented Guided Inquiry Learning activities for her classes for about 6 years. Over the past 4 years, she has served as a POGIL workshop facilitator. Contact e-mail: troutl@lancastercountryday.org*

Chris Lee *has been teaching chemistry for 11 years and also serves as Student Data Analyst, Science Department Chair, and instructional coach for Fort Collins High School, in Fort Collins, CO. He has been involved in advancing inquiry in chemistry education through part-time research with the Colorado State University, Department of Chemistry, and now serves on the Board of Advisors for the Hach Scientific Foundation. Contact e-mail: jolee@psdschools.org*

Rick Moog *is professor of chemistry at Franklin and Marshall College and is the project coordinator for the National Science Foundation-funded Process-Oriented Guided Inquiry Learning (POGIL) Project (DUE-0231120, 0618746, 0618758, 0618800). He has coauthored POGIL materials for college-level general chemistry and physical chemistry and is coeditor of the ACS Symposium Series Book Process-Oriented Guided Inquiry Learning. Contact e-mail: rick.moog@fandm.edu*

Dawn Rickey *is an associate professor of chemistry at Colorado State University, where her research focuses on the relationships among metacognition (monitoring and regulation of one's own thinking), conceptual change, and the ability to solve novel (transfer) problems in chemistry. Dawn codeveloped the Model-Observe-Reflect-Explain (MORE) Thinking Frame as part of her graduate work at University of California, Berkeley. Contact e-mail: rickey@lamar.colostate.edu*

Over the past century, there has been an increasing accumulation of evidence on the effectiveness of inquiry approaches to science instruction at all levels. In this chapter, the principles of inquiry are presented as they relate to the *National Science Education Standards* (NSES) (NRC, 1996), along with a discussion of the research results that support this approach. This is followed by a description of how inquiry-based learning experiences differ from traditional instruction and some suggestions for how to implement inquiry approaches successfully in the high school science classroom. The chapter ends with a more detailed description of two current, research-based examples of effective inquiry pedagogies, Process-Oriented Guided Inquiry Learning (POGIL) and the Model-Observe-Reflect-Explain (MORE) Thinking Frame.

What Is Inquiry Learning?

Inquiry refers to the evidence-based process that scientists engage in to study and propose explanations about aspects of the natural world. When applied to students in science classrooms, *inquiry learning* generally indicates student participation in activities and thinking processes similar to those employed by scientists. The NSES (NRC, 1996) emphasize three important and interrelated learning goals for all students studying science: learning about the nature of science and the work that scientists do; learning to do science (i.e., developing the abilities to design and conduct scientific investigations); and understanding scientific concepts and principles. Since all three of these aspects of science learning can be facilitated by engaging students in inquiry learning, the NRC considers inquiry to be both science content and an exemplary method of teaching and learning science.

Specifically, for students in grades 9–12, the NSES indicate that the fundamental cognitive abilities necessary for students to do scientific inquiry are

- identifying questions and concepts that guide scientific investigations;
- designing and conducting scientific investigations;
- using technology and mathematics to improve investigations and communications;
- formulating and revising scientific explanations and models using logic and evidence;
- recognizing and analyzing alternative explanations and models; and
- communicating and defending a scientific argument.

Developing these abilities requires students to integrate skills such as observation and inference with content knowledge, scientific reasoning, and critical and reflective thinking to enhance their understanding of science.

In addition, according to the NSES, the fundamental understandings about scientific inquiry that students should develop during grades 9–12 are

- Scientists usually inquire about how physical, living, or designed systems function.
- Scientists conduct investigations for a wide variety of reasons.
- Scientists rely on technology to enhance the gathering and manipulation of data.
- Mathematics is essential in scientific inquiry.
- Scientific explanations must adhere to certain criteria; for example, a proposed explanation must be logically consistent, it must abide by the rules of evidence, it must be open to questions and possible modification, and it must be based on historical and current scientific knowledge.
- Results of scientific inquiry—new knowledge and methods—emerge from different types of investigations and public communication among scientists.

In part because of the breadth of the science teaching standards recommended in the original NSES document, an addendum entitled *Inquiry and the National Science Education Standards* (NRC, 2000) distilled this information into five essential features of inquiry that must be integrated into science teaching at all levels to meet the standards. Science teaching and learning sequences that meet the NSES engage students in

- investigating scientifically oriented questions;
- establishing criteria for evidence;
- proposing explanations;
- evaluating explanations; and
- communicating explanations.

Although it is important for students to generate *some* of the scientific questions that they investigate during each of their secondary science courses, they need not always (or even most of the time) generate these questions. The key is for students to be engaged in the five processes listed above.

Forms of Inquiry Instruction and Their Effectiveness. Although inquiry-based instructional methods are defined by engaging students in the construction and evaluation of scientific explanations based on evidence, it is important to note that a wide variety of instructional methods are labeled as “inquiry” by instructors and science education researchers, and that all are not equally effective for promoting student understanding. For example, instructional methods termed “open inquiry” usually involve students designing their own experiments to address some general topic, while those labeled “guided inquiry” or “discovery” usually involve students looking for patterns in data collected via given experimental procedures. Unfortunately, such terms are not always used consistently, so it is important for teachers to work to understand what a particular instructional method entails, ensuring that it incorporates the five key aspects of inquiry emphasized by the NSES, before making the decision to adopt it for their science classes.

In addition, along the continuum of instructional philosophies from teacher-controlled, didactic teaching (found in traditional lectures and “cookbook” laboratory experiments, for example) to student-controlled discovery learning, guided approaches have been shown to maximize the likelihood that students will reflect upon relevant concepts and engage in processes that promote better understanding (Hofstein, 2004; Hofstein and Lunetta, 1982; Lazarowitz and Tamir, 1994; Rund et al., 1989). Studies of students’ understanding of science ideas after instruction provide clear evidence that traditional, didactic teaching methods are not very successful in bringing about productive changes in students’ conceptions (Bodner, 1991; Cros et al., 1986, 1988; Gabel et al., 1987; Gunstone and White, 1981; Nakhleh, 1992; Smith and Metz, 1996). Although didactic styles of instruction can be reasonably successful in imparting the facts, rules, procedures, and algorithms of a domain, they are not effective for helping students refine and build on their ideas about science concepts, in part, because they neither require nor encourage high levels of metacognition (thinking about their own thinking) on the part of the students (Rickey and Stacy, 2000). Typically, students are simply told the “correct” scientific ideas and are expected to understand them, despite the fact that they are given few opportunities and little guidance to develop such an understanding.


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At the opposite end of the spectrum are “pure” discovery-learning approaches to instruction. Proponents of pure discovery believe that students should be encouraged to explore their environments creatively and that these explorations should not be curriculum driven, but based on the interests of the students (Papert, 1980). However, as with didactic approaches, discovery learning methods also fail to encourage student reflection. In fact, unguided discovery-learning methods rely on the assumption that students already possess advanced metacognitive abilities (White, 1992; Vye et al., 1998). Students in highly unstructured environments are never forced to confront their misconceptions nor are they given the opportunity to reconcile them with scientific conceptions. In addition, pure discovery methods lack sufficient guidance, and students may end up confused, not knowing what to do for long periods of time. In fact, a high degree of open-endedness in chemistry laboratory classes has been found to be significantly *negatively* correlated with achievement on chemistry examinations (Riah and Fraser, 1998).

As discussed in more detail below, the goal of a guided learning environment is to strike an appropriate balance between didactic teaching and discovery learning, allowing students to take a large measure of responsibility for their own learning, but also requiring them to reflect upon and explain their ideas, and to justify their use of evidence as well as their conclusions. Students should ultimately be challenged to think about what to do and how to do it, but given enough instructional support along the way so that they do not flounder. The challenge is to develop curricula and instructional methods such that the optimal amount of support is provided for each student. Both the Process-Oriented Guided Inquiry (POGIL) and Model-Observe-Reflect-Explain (MORE) inquiry methods, discussed in detail later in this chapter, are designed to support guided discovery in chemistry learning.

How Inquiry Instruction Differs From Traditional Chemistry Instruction. Although inquiry-based chemistry courses have taken varied forms, all depart from the traditional teaching method in which there is a presentation of scientific principles followed by experiments to verify those principles. Traditional high school chemistry courses are typically broken down into separate lecture and laboratory components. In lecture mode, the instructor usually presents concepts to be learned, while the students listen and take notes. Students may also ask a few questions, but the participation of students in constructing scientific explanations is usually minimal.

After a concept has been presented in class, it is typically reinforced through a laboratory exercise. Traditionally, students perform a "cookbook"-style procedure that has been selected by the instructor, record data into their notebooks (or into empty spaces on a report form), and calculate values that confirm what the instructor has previously presented in the lecture. This method of laboratory instruction does not provide students with opportunities to engage in the key inquiry activities of proposing, evaluating, and communicating explanations for the chemical phenomena they investigate in the laboratory. It also does little to deepen students' understanding of the phenomena under study (Hofstein, 2004; Hofstein and Lunetta, 1982). In contrast (as will be illustrated with examples using POGIL and MORE), inquiry learning engages students in *constructing* evidence-based explanations, as opposed to simply *receiving* or *confirming* scientists' explanations of chemical phenomena.

In an inquiry-based classroom, because of the emphasis on students developing explanations based on evidence, the lecture and laboratory components of a high school chemistry course can become difficult to distinguish one from another. Scientific investigations, driven in part by student ideas, are incorporated into the "lecture" component of class. Whole-class discussions, focused on making sense of experimental observations in terms of what is happening on the molecular level, are commonplace during the "laboratory" component of the class. For example, an introduction to a new topic could begin with the instructor proposing an experiment and asking students to predict what they think will happen. After the instructor performs an experiment as a demonstration, the students would be encouraged to reflect upon what they observed, evaluate their predictions in light of the experimental evidence, and discuss what changes they might want to make to their molecular-level explanations to be consistent with the results of the demonstration. This contrasts with the traditional approach, in which the teacher carries out a demonstration and explains the results to students without involving them in the process of proposing, evaluating, and refining their own scientific explanations based on evidence.

Process-Oriented Guided Inquiry Learning

Process-Oriented Guided Inquiry Learning, or POGIL, is an instructional paradigm based on many of the research-based principles of effective instruction described previously. A POGIL classroom or laboratory experience is characterized by several common components:

- students work in small groups (usually of 3 or 4) and they generally have assigned roles;
- the instructor's role is that of a facilitator, rather than a lecturer;
- the students work on activities that have been specifically and carefully designed, usually

based on the Learning Cycle Approach (Abraham, 1998, 2005; Lawson, 1995; Lawson et al., 1989); the activities are not just "hard problems from the end of the chapter" that the students work on together; and

- the students reflect on their learning and the learning process.

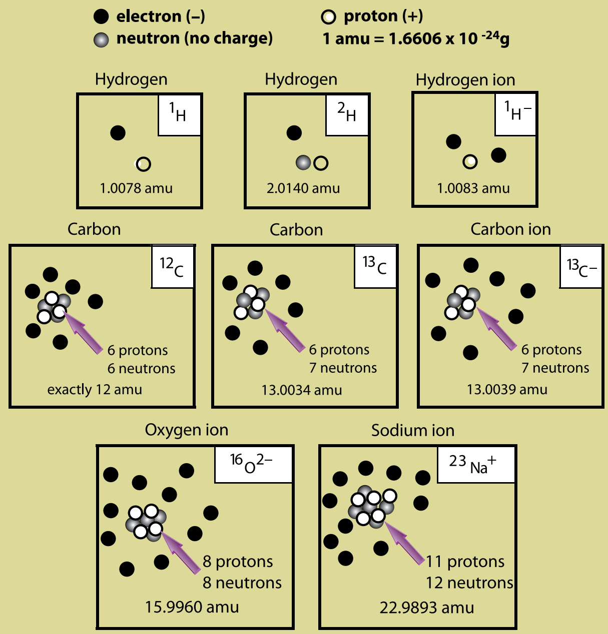
Thus, the goal of POGIL is not only to develop content mastery through student construction of understanding, but also to enhance important learning skills such as critical thinking, problem solving, and assessment.

POGIL activities are typically structured to follow the three phases of the Learning Cycle. In the first phase, "Exploration," students seek a pattern in information presented to (or obtained by) them. A series of carefully designed questions leads the students to make sense of this information and to identify any inherent patterns or trends. In the second phase, "Concept Invention" or "Term Introduction," the guiding questions lead students to develop a concept from the information, and a new term can be introduced to describe this concept. In this way, new terms are introduced *after* the learner has developed a mental construct to which the term is attached. (This contrasts with the typical presentation in a textbook or lecture, in which the introduction of new words commonly occurs first, followed by examples of their use.) Finally, in the "Application" phase, students are required to have an understanding of the concept by applying it in new situations, often requiring the use of deductive reasoning skills (Abraham and Renner, 1986; Lawson, 1999). Thus, this structure guides students to construct their own understandings of a concept, imparting not only a sense of ownership in the process, but also providing the student with insight into the nature of scientific inquiry.

An example POGIL activity designed to introduce the components of an atom will clarify these ideas (Moog et al., 2006). Typically, a lecturer would tell students that atoms are composed of protons, neutrons, and electrons, and that the number of protons in the atom is known as the "atomic number" and determines the atom's identity. A POGIL activity dealing with these ideas is very different. The activity (see Figure 1) begins with a series of diagrams providing examples of a number of atoms, identifying the corresponding element and the number and location of the protons, neutrons, and electrons in each. Through a series of guiding questions, the students are led to recognize that all of the atoms with the same number of protons are identified as the same element (for example, six protons in the case of carbon). They would also note the correspondence of this number (6) with the number on the periodic table that identifies carbon. Only at this point, after the concept has been developed, would the term "atomic number" be used to describe the number of protons in one atom of a given element. In this way, an "exploration" of the information presented in the diagrams allows each student to develop the

Figure 1. An example POGIL activity. [adapted from R. S. Moog and J. J. Farrell, Chemistry: A Guided Inquiry, 3rd Edition. 2006. John Wiley & Sons: Hoboken, NJ. [Used with permission]

The Atom



The **nucleus** of an atom contains the protons and the neutrons.
amu, atomic mass units.
^{1}H and ^{2}H are **isotopes** of hydrogen. ^{12}C and ^{13}C are **isotopes** of carbon.

Critical Thinking Questions

1. How many protons are found in ^{12}C? ^{13}C? $^{13}C^-$?
2. How many neutrons are found in ^{12}C? ^{13}C? $^{13}C^-$?
3. How many electrons are found in ^{12}C? ^{13}C? $^{13}C^-$?
4. a) What feature distinguishes a neutral atom from an ion?
   b) Provide an expression for calculating the charge on an ion.
5. On the basis of the model,
   a) what do all carbon atoms (and ions) have in common?
   b) what do all hydrogen atoms (and ions) have in common?
   c) How many protons, neutrons, and electrons are there in one atom of $^{1}H^+$?
6. The number above each atomic symbol in the periodic table is called the atomic number. What is the significance of the atomic number?
7. On the basis of your answer to CTQ 6, what do all nickel (Ni) atoms have in common?
8. What structural feature is different in isotopes of a particular element?
9. The mass number, A, is the left-hand superscript next to each atomic symbol, as shown in the model. How is the mass number determined (from the structure of the atom)?
10. Where is most of the mass of an atom, within the nucleus or outside of the nucleus? Explain your reasoning using grammatically correct English sentences.

Figure 2. An activity to construct representations of some atoms and ions.

Building Atom Models

In class today, you will build models of several atoms. These models will be used in later classes to explore how the number of protons, neutrons, and electrons in an atom affect the atom's identity and properties. As you build your models, you may notice patterns in the numbers, but it is not expected that you fully understand why these patterns exist or what the consequences of them are.

In the materials packet provided, you should find:

3 permanent markers	40 red beads	43 metal beads
8 small zip-top baggies	41 blue beads	

1. The chart below lists the number of protons, neutrons, and electrons in several atoms. Divide the work evenly among group members so that each person is building only a few atoms. You need one complete set of models for your group when you are finished.

	Symbol	Atomic Mass (amu)	No. of Protons	No. of Neutrons	No. of Electrons
Hydrogen atom(a)	^{1}H	1.0078	1	0	1
Hydrogen atom(b)	^{2}H	2.0140	1	1	1
Hydrogen ion	$^{1}H^{-}$	1.0083	1	0	2
Carbon atom(a)	^{12}C	12.0000	6	6	6
Carbon atom(b)	^{13}C	13.0034	6	7	6
Carbon ion	$^{13}C^{-}$	12.0000	6	7	7
Oxygen ion	$^{16}O^{2-}$	15.9960	8	8	10
Sodium ion	$^{23}Na^{+}$	22.9893	11	12	10

2. Using a permanent marker, label each baggie with an atom's Symbol and Atomic Mass (in amus).
3. Add the appropriate number of items to the baggie to represent the atom's structure. Be sure to count carefully, as these models will be used for activities later.

   Red Beads = Protons   Blue Beads = Neutrons   Metal Beads = Electrons

4. Examine the set of models and discuss any patterns you see with group members. Record your findings here.
5. Scientific models always have limitations. In what ways are the models you built a good representation of atomic structure? In what ways are the models you built a poor representation of atomic structure? (Consider the number, relative sizes, location, and charges of the subatomic particles.)
6. How could these models be improved to better represent the actual structure of atoms?

concept that the number of protons determines the identity of an element; the term "atomic number" is then introduced *following* this construction. The "application" of this concept would be to use the periodic table to identify the number of protons characterizing other elements. Alternatively, the activity could begin with groups of students using beads of different colors and sizes to represent protons, neutrons, and electrons in atoms. The students construct atom models by placing the beads in plastic sealed baggies using specific instructions on how many proton, neutron, or electron beads to place in the bags (see Figure 2). In essence, the students produce the "data" that will be explored. Then (possibly the next day), the bags are used to work through an activity similar to Figure 1.

There are two key aspects to the design of any POGIL classroom activity. First, appropriate information must be included for the initial "Exploration," so that students are able to develop the desired concepts. Second, the guiding questions must be carefully constructed and sequenced to enable students to reach the appropriate conclusion, while at the same time encouraging the development of various process skills. Having them reconstruct a table with the data in a certain order, or having them draw a graph and describe the relationship often helps them see patterns in the data more readily. An example involving the use of a pressure probe to investigate the pressure-volume relationship in gases is provided in Figure 3.

The POGIL philosophy is that the development of key process skills (information processing, problem solving, critical thinking, communication, teamwork, self-assessment) is a specific focus of the classroom implementation. POGIL uses course content to facilitate the development of important process skills, including higher-level thinking and the ability to learn and to apply knowledge in new contexts. This approach provides an excellent opportunity to develop most of the key inquiry skills (establishing criteria for evidence; proposing, evaluating, and communicating explanations) in the context of developing content knowledge and investigating questions of scientific interest. Numerous resources are available, providing further information about implementing POGIL (Hanson, 2006; POGIL Project, 2008; Moog et al., 2008).

Although some college courses are taught virtually exclusively using the POGIL approach (Farrell et al., 1999), many high school teachers have found that POGIL activities work best when combined with other methods of instruction. Using POGIL activities as one of a number of classroom techniques can help address the multiple learning styles present in any classroom. For example, one of the authors (Trout) uses a POGIL activity at least once every two weeks, usually at the beginning of a lesson or unit to introduce key concepts. This often provides a strong conceptual foundation, leading to a reduction in the need for review and repetition later in the unit, or the course.

It bears noting that because of the great diversity in student ability, the group interactions of POGIL can present significant challenges. The literature on effective implementation of cooperative and group learning is vast and will not be addressed here. Johnson et al. (1991), Cooper (2005), and Felder (2008) provide excellent resources on this subject, as does the POGIL Instructor's Guide (Hanson, 2006).

Some teachers remain skeptical about using POGIL with high school students. Common remarks include "They don't have enough background knowledge." or "They are not mature enough." In addition, some instructors are concerned about the large quantity of material that must be presented: "I need to cover so much material for standardized testing, I can't afford time for inquiry learning." However, many high school teachers have found that the constructivist approach that POGIL uses is a perfect fit for high school. In fact, the learning cycle structure used in POGIL activities was originally developed for concrete learners in elementary schools. This approach provides students with a solid foundation of scientific thought processes and content. Research has documented the effectiveness of the Learning Cycle Approach in high school science classes (Abraham, 2005) and also the effectiveness of POGIL in a variety of settings (Farrell et al., 1999; Hanson and Wolfskill, 2000; Lewis and Lewis, 2005; POGIL Project, 2008). Teachers who have implemented POGIL in their high school classrooms report great success with difficult topics at basic, regular, and honors levels. Students tend to understand these concepts better, and retain the understanding longer than with previous methods. They are developing the skills of analysis, thought, and communication that are at the heart of inquiry learning. In addition, the students are learning to work as a group, organize information, find patterns, and construct their own, deeper, understanding of concepts.

The Model-Observe-Reflect-Explain Thinking Frame

A second example of a research-based instructional tool that promotes inquiry learning in the chemistry classroom is the Model-Observe-Reflect-Explain, or MORE, Thinking Frame. MORE provides students with a framework for thinking like a chemist engaged in inquiry. Originally designed to be used with multiweek laboratory investigations to facilitate students' successive refinements of their explanations about chemical phenomena (Tien et al., 1999), the MORE Thinking Frame can also be used to transform standard chemistry laboratory experiments and demonstrations into cognitively effective inquiry experiences that incorporate the five essential features of inquiry identified in *Inquiry and the National Science Education Standards* (NRC, 2000).

Using **MORE**, students are first asked to describe their initial understandings (their initial **models**) about the chemical

Figure 3. An activity to investigate Boyle's law.

Investigation of Gas Properties

Samples of gases can be described by several variables, which are all interrelated. We can take the **temperature** of a gas sample, measure the **pressure**, and find the **volume** or the **mass**. As you may have experienced, when you heat a gas sample, its volume changes, or perhaps its pressure. Is there a specific mathematical relationship between these variables? This activity will look at the relationship between volume and pressure specifically, while keeping mass and temperature the same.

Set up a computerized gas pressure probe as instructed. Connect a syringe, about half full of air, to the pressure probe.

1. What is the pressure inside the syringe? What units are you using?
2. Move the plunger on the syringe in and out without creating a leak. Observe the changes in pressure as you do this. Explain **on the molecular level** why the pressure changes.
3. Identify the variables in this activity.

   Independent Dependent Controlled
4. Fill in a data table with 10 sets of pressure-volume readings.

   (Data table is provided for students to fill in.)
5. Describe in general the trend or relationship between the variables.

   "As the volume gets smaller, the…."
6. Plot the points of data that you just collected on a sheet of graph paper. Which axis should you label with your independent variable? Which axis is the dependent variable?
7. Scientists often create a model for data using a mathematical relationship. Consider the following types of relationships. What is the basic equation for each? What would a plot of the relationship look like?

   (Hint: Use a graphing calculator to graph each one if you don't remember the shape of the graph.)

   Linear Inverse Exponential
   $y = mx + b$
8. Which of the above mathematical models would best fit the plot made with your pressure and volume data?
9. Write an equation, using the variables V and P (instead of x and y) for your data.

Figure 4. Initial model assignment for "The Chemistry of Antacids: How do YOU Spell Relief?" laboratory module, and an example of a high school student's initial model.

Initial Model Assignment

Describe, in words and/or pictures, your understanding of how an antacid works. What do you expect to observe with your senses before and after you (or another person) take an antacid to relieve heartburn or indigestion? Also show how you think an antacid would affect the pH of the stomach contents over time. This is your initial macroscopic model. Then explain what you think the molecules, atoms, and/or ions are doing that results in your observations; this is your initial molecular-level model.

An Example of a High School Student's Initial Model

"An antacid is a more basic substance that will try to neutralize or raise the pH of the acid in the stomachs. The antacids break the acid particles apart to make the molarity lower. When the antacid, if it is a base, is added to the acid in the stomach, they would make water and salt as a product. [Student drawing showing antacid being added to stomach, and water and salt as products.]

Stomach acid (acid) + antacid (base) → H_2O (water) + Salt

The smaller the molarity of the acid, the less harsh it will be, Therefore, when the molarity is lowered, it will lower the pH and relieve the pain it is causing.

Important characteristics of effective antacids

pH level, the higher the better; chewable, swallowable, or liquid; molarity, higher pH; size, lower surface area = higher rate of reaction; type of based used. The acid will start out with a high level of hydronium or H_3O^+, and to neutralize it, hydroxide or OH^- must be added. When using an antacid, when it reacts, would it fizz and bubble? Would the fizzing and bubbling have anything to do with LeChatlier's theory?"

system that they will investigate. In these initial models, typically submitted as written prelaboratory assignments, students are encouraged to use words and pictures to describe their understandings from both macroscopic (what students expect to observe and/or measure) and molecular-level (what students think atoms, molecules, and/or ions are doing that would result in the expected observations) perspectives. Pictures are especially useful for communicating molecular-level understandings. (An example of an initial model assignment given to students, and a corresponding student model, is shown in Figure 4.) Student models are then presented and discussed, either in small groups or as a whole class; this makes students aware of alternative understandings and explanations. Next, students gather evidence, typically in the form of experimental observations and/or measurements, which is expected to inform their initial models (**observe**). Third, students monitor the progress of their experiments, seek to understand what is happening, and consider the implications of the evidence being collected as it relates to their initial models (**reflect**). Fourth, students use their evidence to construct a scientific explanation of why their previous model has changed (or why it has not) for presentation to their teacher and other members of the class (**explain**). Following each experiment, students are explicitly prompted to reflect upon the implications of the evidence they have gathered for their model and revise their ideas accordingly (model refinement). Throughout this inquiry process, the essence of chemistry—making connections between macroscopic observations and atomic- and molecular-level explanations—is emphasized. Thus, the MORE Thinking Frame provides cognitive guidance and support for students as they propose, communicate, evaluate, and refine their own evidence-based explanations to address scientifically oriented questions. It provides students with a framework for *thinking like a chemist* engaged in inquiry, in contrast to traditional laboratory exercises that typically focus on providing students with instructions for carrying out physical manipulations in the laboratory.

By virtue of constructing and refining their models in light of the evidence that they gather, students using the MORE Thinking Frame engage in all five of the essential features of inquiry learning, including investigating scientifically oriented questions, proposing explanations, establishing criteria for evidence, and evaluating and communicating explanations. In addition, the MORE Thinking Frame combines a focus on metacognition (thinking about one's own thinking) with many interrelated elements that research has found to be among the most effective for enhancing science learning. These elements include activating students' prior knowledge (Alvermann and Hynd, 1989; Marazano et al., 2001), encouraging students to combine linguistic and nonlinguistic modes to represent their understanding (Marazano et al., 2001; Mayer, 1989), promoting testing and revision of models (Marazano et al., 2001; White, 1993, 1998), fostering cognitive conflict or dissatisfaction with naïve conceptions (Guzzetti et al., 1993), and scaffolding students' engagement in authentic scientific thinking processes (Brown and Campione, 1994; Collins et al., 1989).

Implementing the MORE Thinking Frame in High School Chemistry Classrooms

Implementing MORE in the high school chemistry classroom can be very rewarding, for both the student and the teacher, and at the same time, somewhat challenging for first-time practitioners. While being extremely beneficial to learning, the MORE framework takes additional time to both implement in the classroom and to check for student understanding (grading). In the beginning, instructors may find implementation challenging, but after sufficient experience with it, they often question whether their students really ever learned without it. Using the MORE method in the laboratory is so successful that instructors often start to use aspects of it in their “lectures”, and the traditional separation between lecture and laboratory blurs. Instructors begin to ask students higher-level questions that require reflection upon and explanations of what students think is happening on the molecular level. Teachers begin to spend less time presenting what they know of chemistry to students, and become more concerned with what and how their students think. When instructors implement MORE, learning starts to happen on a deeper level for both students and teachers.

To compare and contrast traditional laboratory methods with MORE, we explore the differences between a typical acid-base laboratory experiment and a MORE laboratory module focused on constructing evidence-based explanations of how antacids work. In the traditional acid-base laboratory experiment, students typically add acid-base indicators to various substances, including various solutions from the stockroom, as well as household chemicals. Students then record data into their lab notebooks and answer a set of questions relating to the substances’ pHs (if any questions are present at all). Students are graded on how close they come to the solutions’ accepted pHs and how well they answered the required questions. An extension might be added later, in which the students use titrations to figure out the concentration of an unknown acid or base solution.

A MORE laboratory investigation that is intended to foster an understanding of the concepts and principles of acid-base chemistry looks quite different than the traditional one, and the resulting learning outcomes are very different too. For example, in a MORE laboratory module entitled “The Chemistry of Antacids: How do YOU Spell Relief?”, students are first asked to propose an explanation for how antacids work. In these initial models, students are asked to explain what they think they will observe on the *macroscopic* level when they add antacids to the stomach, and to provide their ideas about what happens on the *molecular* level that explains these observations. (See Figure 4 for the full initial model assignment.) A whole-class discussion of the students’ initial models then follows, allowing students the opportunity to communicate their explanations and compare their ideas with those of other students.

After the students discuss their initial models, they are guided through investigations such as finding the change in pH when adding an antacid to a simulated stomach, relative solubilities of different antacids and effects of solubility on pH, and determining the antacid- neutralizing capacities of the different antacids. When conducting their experiments (which are primarily designed by the students themselves), students are encouraged to discuss their findings with their peers and to reflect on how the evidence they have gathered relates to their initial ideas. To stimulate this student reflection, the teacher poses questions to groups of students. Some general questions that we have found effective include

- What is the goal of this experiment?
- How does what you are doing contribute to the goal of the experiment?
- How does what you are currently observing relate to your initial model?
- Are your observations consistent with your initial model? Explain.
- Does your model fully explain your observations? How?
- What do you think is happening on the molecular level?
- What doesn’t make sense to you?

After each experiment, students evaluate their initial explanations in light of the experimental evidence they have collected, refine their models of antacids based on what they have observed, and discuss their refinements with the class. After several cycles of experimentation, students write a final refined model that not only includes their final explanation of how antacids work, but also information about each refinement they have made to their models along the way. (See Figure 5 for excerpts from the final refined model for the student whose initial model appears in Figure 4.) The students' models are not assessed on how scientifically correct their explanations have become, but rather, on how consistent their claims are with the evidence they have gathered. An important point to note is that to encourage this kind of work from students effectively, instructors must move away from thinking that students ideas always need to be *fully* correct. Rather, MORE instruction emphasizes the process of students constructing explanations that are consistent with the evidence they have gathered, which should ultimately lead to understandings consistent with the scientifically accepted views. As you can see from Figures 4 and 5, the student productively refines their model of how antacids work, both from macroscopic and molecular-level perspectives, but their molecular-level views are not yet fully correct by the time they write their final model. Clearly, teachers obtain important feedback about students' developing understandings from reading their students' models that they would not be able to obtain from reading traditional laboratory reports.

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In addition to presenting the refined model (from both macroscopic and molecular-level perspectives), research on the use of the MORE Thinking Frame has shown that it is very important for students' understanding of the chemistry concepts for them to explicitly *explain why their model has changed* (or why it has not if the experimental evidence supports the initial model), using specific experimental evidence. For example, in the refined model shown in Figure 5, the student wrote, "We discovered that the most effective antacids have calcium carbonate as their main active ingredient. This means it won't create a salt and water but instead it will create water, carbon dioxide, and a salt is created. This would explain why the product bubbles and fizzes." Although we would like to see the model expressed in a bit more detail, this student is explaining that their ideas changed from thinking that an antacid must contain hydroxide (OH^-) and wondering whether that would lead to the macroscopic observation of fizzing and bubbling (see Figure 4) to understanding that an active ingredient in many antacids is carbonate (CO_3^{2-}), which is consistent with the observation of bubbles of carbon dioxide gas when the antacid is added to acid. These model changes were based on gathering data from antacid labels and from observations made when adding various antacids to aqueous acid solutions. Thus, the student is using evidence to refine their explanation of how antacids work and communicate an awareness of how their ideas changed as a result of participating in scientific inquiry.

Research on the use of the MORE Thinking Frame in high school chemistry classes reveals that students participating in MORE laboratory experiences outperform control groups participating in more traditional laboratory experiences on written chemistry examinations. In addition, preliminary video analyses indicate that two main aspects of MORE activities prompted student molecular-level discussions at the high school level: classroom model writing and instructor questioning during the experimental portion of the class period (Carillo et al., 2005). Student survey and interview data also show that, in contrast to students in standard classes, students participating in MORE inquiries learned to value thinking about what is happening on the molecular level to explain their observations.

Implementing Inquiry *Effectively* in the High School Classroom

The experience of teaching chemistry through inquiry, and what is required of the teacher, is very different compared with teaching via traditional methods, in part because the students' ideas often dictate the direction that class discussions and experimental investigations will take. Teachers using inquiry in the classroom need to constantly adjust pacing and follow the students' lead to some extent, not simply proceed through lecture notes. For many instructors, the change to inquiry instruction from more traditional approaches provides numerous challenges, particularly for those who have not experienced inquiry as a student or had training in its effective implementation.

Even though there is a great deal of research indicating that inquiry approaches can be very effective, this does not guarantee that every attempt at inquiry will be successful. In fact, some instructors may be leery of implementing inquiry because of prior experiences in which the "recommended" approach was to provide students with access to various materials and "let them loose" to explore on their own - in hopes that they would "discover" some pattern or scientific principle and be able to explain it. This approach frequently leads to arguments against inquiry from teachers: "I can't afford the time." "Students don't have the natural ability they need for inquiry." "Students don't have the necessary background." The problem is that the inquiry experiences on which these opinions are based likely were not constructed with enough student guidance to achieve the goals that were intended.

For many instructors, the logical place to consider implementing inquiry instruction is in the context of a laboratory setting. Laboratory-based projects (such as a science fair investigation), in which the student independently selects the topic and the question to examine, provide the typical example of an open-inquiry experience. Many teachers' reaction to inquiry-based labs is disdain for the chaos they create in the classroom. Using a guided approach in which the students are asked to formulate a question within a topic, design an experimental protocol to gather evidence to address their question, and construct an evidence-based explanation of their results offers a happy medium. For example, if the topic is kinetics, the students can be asked to hypothesize what variable they might alter to increase the rate of a particular reaction. Students will come up with several different questions and procedures, but the instructor only needs to prepare one system of reactants and materials. There may be some extra preparation required to set up equipment (for example, one group might need a hot plate, while another needs ice), but the chaos is limited. While many instructors have found that laboratory experiments take more time, guided inquiry ultimately provides better educational outcomes when students plan (at least part of) the procedure themselves, and perhaps ask their own questions, but the focus is on guiding students in proposing, evaluating (based on the evidence they collect), and communicating a scientific explanation.

Inquiry learning need not be limited to the realm of the laboratory. For example, data or manipulatives may be provided to the students in place of results from a laboratory investigation. If appropriate information is provided and is accompanied by a carefully crafted

Figure 5. Excerpts from student's final refined model for "The Chemistry of Antacids: How do YOU Spell Relief?" laboratory module. (Same student whose initial model is shown in Figure 4.)

An Example of a High School Student's Final Refined Model

"On the macroscopic level the main thing we can see is fizzing and bubbling. The color also changed because of the pH indicator. When we started, the acid had a very low pH and the antacid always significantly raised the pH … On the molecular level, when the basic molecules come into contact with the acidic ones, they break each other apart and form a substance. We discovered that the most effective antacids have calcium carbonate as their main active ingredient. This means it won't create a salt and water but instead it will create water, carbon dioxide, and a salt. This would explain why the product bubbles and fizzes. [Student drawing showing bubbles labeled "CO_2" rising from a container of liquid. The liquid phase is labeled "H_2O + salt."] I am not sure what the actual antacid particles look like on a molecular level, but I am guessing the antacid particles are attracted to the acid particles to even the pH out. The antacid particles come between the acid particles and reattach with their polar matched ion. [Student drawing showing reactants composed of Ant^+Ant^- and H^+Cl^- and products composed of Ant^+Cl^- and H^+Ant^-] These antacids don't necessarily contain hydroxide but more often contain a type of carbonate. It is true that the lower the original molarity of the acid, the easier and faster the pH will raise. We were unable to test the pH of the antacid before, so we don't know the original pH of the antacids ..."

set of questions leading the students through the logical progression necessary to understand a concept, then the inquiry learning experience can be powerful, particularly in developing the students' abilities in proposing, evaluating, and communicating logical and evidence-based explanations of their thinking. The activity described previously in Figure 2 provides an example of this type of approach.

A number of approaches to inquiry instruction for the physical sciences at the high school and introductory college levels that have been classroom-tested and shown to be effective are now widely used. Among these are the Physics by Inquiry program from the University of Washington (McDermott, 1996*)*; the Modeling Instruction Program for physics, chemistry, and physical sciences from Arizona State University (Modeling Instruction Program, 2008); Living by Chemistry from the University of California at Berkeley (Stacy, 2008); the Science Writing Heuristic approach to laboratory experiences and report writing (Greenbowe and Hand, 2005); and the Discovery Chemistry curriculum from the College of the Holy Cross (Ditzler and Ricci, 1991, 1994; Ricci et al., 1994).

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Incorporating inquiry-based instructional methods, such as Process-Oriented Guided Inquiry (POGIL) and the Model-Observe-Reflect-Explain (MORE) Thinking Frame, in the high-school chemistry classroom facilitates students' learning of how to investigate chemical problems, as well as understanding the process and nature of chemistry, leading to more robust understandings of chemistry content.

Recommended Readings

Carillo, L.; Lee, C.; Rickey, D. Enhancing Science Teaching by doing MORE: A Framework to Guide Chemistry Students' Thinking in the Laboratory. *Sci. Teach.* (Special Issue: Inquiry in the Laboratory) 2005, *72*, 60–64. The article discussing the use of the MORE Thinking Frame in high school chemistry classes provides additional examples to supplement those presented here.

Moog, R. S.; Creegan, F. J.; Hanson, D. M.; Spencer, J. N.; Straumanis, A. R. Process-Oriented Guided Inquiry Learning. *Metro. Univ. J.* 2006, *17,* 41–51. This article provides a general overview of POGIL and contains many additional references.

National Research Council (NRC). *Inquiry and the National Science Education Standards;* National Academies Press: Washington, DC, 2000. This addendum to the NSES focuses on the essential features of integrating inquiry learning into science instruction.

Recommended Web Sites

http://more.colostate.edu/ This Web site provides information about using the Model-Observe-Reflect-Explain (MORE) Thinking Frame, including contact information for developers and implementers of MORE. (accessed March 2008).

http://www.pogil.org/ This Web site provides information about Process-Oriented Guided Inquiry (POGIL), including data about the effectiveness of the approach, a downloadable version of the Instructor's Guide to POGIL, and information on upcoming workshops and other events. (accessed March 2008).

References

Abraham, M. R. The learning cycle approach as a strategy for instruction in science. In *International Handbook of Science Education;* Tobin, K., Fraser, B., Eds.; Kluwer: The Netherlands, 1998; pp 513–524.

Abraham, M. R. Inquiry and the learning cycle approach. In *Chemists' Guide to Effective Teaching;* Pienta, N. J., Cooper, M. M., Greenbowe, T. J., Eds.; Prentice Hall: Upper Saddle River, NJ, 2005.

Abraham, M. R.; Renner, J. W. Research on the learning cycle. *J. Res. Sci. Teach.* 1986, 23, 121–143.

Alvermann, D. E.; Hynd, C. R. Effects of prior knowledge activation modes and text structure on nonscience majors' comprehension of physics. *J. Educ. Res.* 1989, *83*, 97–102.

Bodner, G. M. I have found you an argument: The conceptual knowledge of beginning chemistry graduate students. *J. Chem. Educ.* 1991, *68*, 385–388.

Brown, A. L.; Campione, J. C. Guided Discovery in a Community of Learners. In *Classroom Lessons: Integrating Cognitive Theory and Classroom Practice;* McGilly, K., Ed.; MIT Press: Cambridge, MA; 1994; pp 229–270.

Carillo, L.; Lee, C.; Rickey, D. See Recommended Readings.

Collins, A.; Brown, J. S.; Newman, S. E. Cognitive Apprenticeship: Teaching the Crafts of Reading, Writing, and Mathematics. In *Knowing, Learning, and Instruction: Essays in Honor of Robert Glaser;* Resnick, L. B., Ed.; Lawrence Erlbaum Associates: Hillsdale, NJ, 1989; pp 453–494.

Cooper, M. M. An introduction to small group learning. In, *Chemists' Guide to Effective Teaching*; Pienta, N. J., Cooper, M. M., Greenbowe, T. J., Eds.; Prentice Hall: Upper Saddle River, NJ:, 2005.

Cros, D.; Amouroux, R.; Chastrette, M.; Fayol, M.; Leber, J.; Maurin, M. Conceptions of first-year university students of the constituents of matter and the notions of acids and bases. *Eur. J. Sci. Educ.* 1986, *8*, 305–313.

Cros, D.; Chastrette, M.; Fayol M. Conceptions of second-year university students of some fundamental notions in chemistry. *Int. J. Sci. Educ.* 1988, *10*, 331–336.

Ditzler, M. A.; Ricci, R. W. Discovery chemistry: Balancing creativity and structure. *J. Chem. Educ.* 1994, *71,* 685–688.

Ditzler, M. A.; Ricci, R. W. Discovery chemistry: A laboratory-centered approach to teaching general chemistry. *J. Chem. Educ.* 1991, *68*, 228–232.

Farrell, J. J.; Moog, R. S.; Spencer, J. N. A guided inquiry general chemistry course. *J. Chem. Educ.* 1999, *76*, 570–574.

Felder, R. M. Publications on Cooperative Learning. http://www4.ncsu.edu/unity/lockers/users/f/felder/public/Student-Centered.html#Publications-Coop, 2008. (accessed March 2008).

Gabel, D. L.; Samuel, K. V.; Hunn, D. J. Understanding the particulate nature of matter. *J. Chem. Educ.* 1987, *64*, 695–697.

Greenbowe, T. J.; Hand B. M. Introduction to the science writing heuristic. In *Chemists' Guide to Effective Teaching.* Pienta, N. J., Cooper, M. M., Greenbowe, T. J., Eds.; Prentice Hall: Upper Saddle River, NJ, 2005.

Gunstone, R. F.; White, R. T. Understanding of gravity. *Sci. Educ.* 1981, *65*, 291–299.

Guzzetti, B. J.; Snyder, T. E.; Glass, G. V.; Gamas, W. S. Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education. *Read. Res. Quart.*1993, *28*, 117–159.

Hanson, D. M. *Instructor's Guide to Process Oriented Guided Inquiry Learning*. Pacific Crest: Lisle, IL, 2006. Also available as a download from the POGIL Web site at http://www.pogil.org/resources/pogil_ig.php (accessed March 2008).

Hanson, D. M; Wolfskill, T. Process workshops: A new model for instruction. *J. Chem. Educ.* 2000, *77*, 120–130.

Hofstein, A. The laboratory in chemistry education. *Chem. Educ. Res. Pract.* 2004, *5*, 247–264.

Hofstein, A.; Lunetta, V. N. The role of the laboratory in science teaching: Neglected aspects of research. *Rev. Educ. Res.* 1982, *52*, 201–217.

Johnson, D. W.; Johnson, R. T.; Smith, K. *Active Learning: Cooperation in the College Classroom*, Interaction Book Company: Edina, MN, 1991.

Lawson, A. E.; Abraham, M. R.; Renner, J. W. *A Theory of Instruction: Using the Learning Cycle to Teach Science Concepts and Thinking Skills* [Monograph, Number one]. National Association for Research in Science Teaching: Kansas State University, Manhattan, KS, 1989.

Lawson, A. E. *Science Teaching and the Development of Thinking*. Wadsworth Publishing Company: Belmont, CA, 1995.

Lawson, A. E. What should students know about the nature of science and how should we teach it? *J. Coll. Sci. Teach*. 1999, 28, 401–411.

Lazarowitz, R.; Tamir, P. Research on using laboratory instruction in science. In *Handbook of Research on Science Teaching and Learning*; Gabel, D. L., Ed.; Maxwell Macmillan International: New York, 1994; pp 94–128.

Lewis, S. E.; Lewis, J. E. Departing from lectures: An evaluation of a peer-led guided inquiry alternative. *J. Chem. Educ.* 2005, *82*, 135–139.

Marazano, R. J.; Pickering, D.; Pollock, J. E. *Classroom Instruction that Works: Research-Based Strategies for Increasing Student Achievement*; Association for Supervision and Curriculum Development: Alexandria, VA, 2001.

Mayer, R. E. Models for understanding. *Rev. Educ. Res.* 1989, *59*, 43–64.

McDermott, L. C. *Physics by Inquiry.* New York: John Wiley & Sons, 1996; Vol. I and II.

Modeling Instruction Program. Available online at http://modeling.asu.edu (accessed March 2008).

Moog, R. S.; Creegan, F. J.; Hanson, D. M.; Spencer, J. N.; Straumanis, A. R.; Bunce, D. M.; Wolfskill, T. POGIL: Process-Oriented Guided Inquiry Learning. In *Chemists' Guide to Effective Teaching;* Pienta, N. J.; Cooper, M. M.; Greenbowe. T. J., Eds. Pearson Prentice Hall: Upper Saddle River, NJ, 2008; Vol. 2.

Moog, R. S.; Creegan, F. J.; Hanson, D. M.; Spencer, J. N.; Straumanis, A. R. Process-oriented guided inquiry learning. *Metro. Univ. J.* 2006, *17*, 41–51.

Nakhleh, M. B. Why some students don't learn chemistry. *J. Chem. Educ.* 1992, *69*, 190–196.

National Research Council (NRC). *Inquiry and the National Science Education Standards;* National Academies Press: Washington, DC, 2000.

NRC. *National Science Education Standards*; National Academies Press: Washington, DC, 1996.

Panitz, T. The Case for Student Centered Instruction Via Collaborative Learning Paradigms. Available online at http://home.capecod.net/~tpanitz/tedsarticles/coopbenefits.htm (accessed March 2008).

Papert, S. A. *Mindstorms: Children, Computers, and Powerful Ideas*; Basic Books: New York, 1980.

POGIL Project. Effectiveness of POGIL. Available online at http://www.pogil.org/effectiveness/ (accessed March 2008).

Riah, H.; Fraser, B. J. Chemistry Learning Environment and Its Association with Students' Achievement in Chemistry. Presented at the Annual Meeting of the American Educational Research Association, San Diego, CA, 1998.

Rickey, D.; Stacy, A. M. The role of metacognition in learning chemistry. *J. Chem. Educ.* 2000, *77*, 915–920.

Rickey, D.; Teichert, M. A.; Tien, L. T. Model-Observe-Reflect-Explain (MORE) Thinking Frame Instruction: Promoting Reflective Laboratory Experiences to Improve Understanding of Chemistry. In *Chemists' Guide to Effective Teaching*; Pienta, N. J., Cooper, M. M, Greenbowe, T. J., Eds.; Pearson Prentice Hall: Upper Saddle River, NJ, 2008; Vol 2.

Ricci, R. W.; Ditzler, M. A.; Jarret, R.; McMaster, P.; Herrick, R. The Holy Cross discovery chemistry program. *J. Chem. Educ*. 1994, *71*, 404–405.

Rund, J. V.; Keller, P. C.; Brown, S. L. Who does what in freshman lab? A Survey. *J. Chem. Edu*c. 1989**,** *66*, 161–164.

Smith, K. J.; Metz, P. A. Evaluating student understanding of solution chemistry through microscopic representations. *J. Chem. Educ.* 1996, *73*, 233–235.

Stacy, A. *Living by Chemistry*. Key Curriculum Press: Emeryville, CA, 2008. Available online at http://www.keypress.com/x4716.xml (accessed March 2008).

Tien, L. T.; Rickey, D.; Stacy, A. M. The MORE thinking frame: Guiding students' thinking in the laboratory. *J. Coll. Sci. Teach.* 1999, *28*, 318–324.

Tien, L. T.; Teichert, M. A.; Rickey, D. Effectiveness of a MORE laboratory module in prompting students to revise their molecular-level ideas about solutions. *J. Chem. Educ*. 2007, *84*, 175–181.

Vye, N. J.; Schwartz, D. L.; Bransford, J. D.; Barron, B. J.; Zech, L. SMART environments that support monitoring, reflection, and revision. In *Metacognition in Educational Theory and Practice*; Hacker, D. J., Dunlosky, J., Graesser, A. C., Eds.; Lawrence Erlbaum Associates: Mahwah, NJ; 1988; pp 305–346.

White, B. Y. Thinkertools: Causal Models, Conceptual Change, and Science Education. *Cognit. Instr.* 1993, *10*, 1–100.

White, B. Y.; Frederickson, J. R. Inquiry, Modeling, and Metacognition: Making Science Accessible to All Students. *Cognit. Instr.* 1988, *16*, 90–91.

White, R. T. Implications of recent research on learning for curriculum and assessment. *J. Curr. Stud.* 1992, *24*, 153–164.