In this chapter, we describe how the revolutionary views of Lavoisier’s theory of combustion proposed in the late 1700s were used as a context for a set of interrelated, inquiry-fostering investigations in a high school chemistry class. In addition, we use this example of chemistry inquiry as a case to develop some central ideas about inquiry pedagogy in science classrooms across content areas.

The concept of teaching through inquiry has been discussed in science education for decades and has an extensive history of interpretation (see Chapter 2). In addition, there has been considerable work in the development of frameworks for analyzing science curriculum for its inquiry content. Often, however, inquiry is characterized in terms of idealized standards that focus to a large extent on the degree of student autonomy or authenticity to science practices (NRC 2000).
Understanding the value of inquiry science teaching requires looking beyond the idealized standard and into real classrooms. The question then becomes, “What are the characteristics of inquiry science teaching, and how can a description be captured to support teachers in adopting inquiry pedagogy practices?” Our approach has been to work toward a theory of teaching grounded in practice (Richardson 2000) and, specifically, to use multiple instances of classroom practice to extract elements of classroom inquiry science teaching. We frame the activities described in this chapter in terms of three elements of classroom inquiry science teaching identified from our practice: perplexity, model testing, and synthesis.

All the activities described took place in Mr. Criswell’s (the second author’s) 11th-grade Introductory Chemistry classroom. His overall objective for this series of lessons was for students to develop a model of combustion and recognize its relationship to slower versions of the same process (e.g., rusting). Eventually, students applied their model of combustion to explain how various common fuels burn, which included being able to represent combustion processes in the form of simple word equations.

**Perplexity**

_The best, indeed the only preparation [for learning] is arousal to a perception of something that needs explanation, something unexpected, puzzling, peculiar. When the feeling of a genuine perplexity lays hold of any mind (no matter how the feeling arises), that mind is alert and inquiring._ (Dewey 1910, p. 207)

As Dewey aptly described, if we teachers want our students to engage in science in a meaningful way and develop deep conceptual understandings of phenomena, we need to engender in them a sense of perplexity. However, creating a science classroom that causes students to be perplexed without being confused is a challenging task. It is an even more daunting challenge to navigate when one considers the need to align students’ classroom experiences with their everyday-life experiences. Students are accustomed to complex multithreaded plots in television shows and movies and also multiple simultaneous modes of communication (e.g., talking on the phone while e-mailing and sending instant messages). There is also evidence that more complex learning experiences aid student learning. In contrast, science curriculum tends to be linear. Students often have difficulty making connections between individual daily classroom activities and fail to understand the larger scientific concepts the teacher is using to organize all the disparate activities.
One attempt to address this difficulty is problem-based learning, where curricular activities are organized around questions developed out of an anchoring activity or event. Connecting students’ learning to shared phenomena they have experienced in class helps students understand how individual activities fit into a larger conceptual pattern. Organizing activities in more multithreaded ways may help students develop a more sophisticated conception of science. There may be cognitive, motivational, and other advantages to thinking about curriculum in less linear ways. By organizing instruction in a way that contains multiple threads of activity, some subsets of which are always open for investigation and discussion, teachers can maintain a level of perplexity among their students.

In a traditional chemistry classroom, teachers may have students follow preset experimental procedures to determine known solutions or deliver lectures on differences between physical and chemical change. To develop deep conceptual understanding students must engage with empirical evidence in a way that requires them to both interpret evidence from various sources and make an argument to support a particular interpretation or model (see Chapter 8). If teachers do not engage students in a more complex version of the processes of science, they communicate implicitly that science is linear and unambiguous and has clear answers that are known not only in general but also in particular by the teacher.

Curriculum and pedagogy in science still generally approach science in a linear fashion with activities being designed as a chain, ideally organized to build conceptual understanding in a stepwise fashion from one activity to the next. Students are rarely engaged in multiple, seemingly disparate threads of activity of varying duration over long periods of time, which eventually resolve into different aspects of the same underlying phenomenon.

This type of pedagogical structure—involving complex, interwoven threads of activity—lends itself best to classroom scientific inquiry. Although individual investigations or activities may have clear results, the ways those results connect to other open or closed investigations must be determined by the students. This creates doubt about the validity of ideas and creates perplexity in the form of multiple, sometimes conflicting, activity threads that students are attempting to connect. The hard work of coming to conclusions and weighing evidence rests with the students. Mr. Criswell’s lessons were designed with student perplexity in mind. Students were asked to do testing and synthesis of evidence in the context of creating a model for combustion.

The unit began with students viewing and discussing a video about spontaneous human combustion with the idea of exploring the validity of spontaneous human combustion.
human combustion as a scientific explanation. Mr. Criswell focused students on determining if they considered such supernatural offerings viable and scientific. Whatever the direction of this conversation, Mr. Criswell at no point offered a valid scientific alternative.

A week later students began considering the difference between physical and chemical change, beginning with the idea that chemical changes produce a new substance while physical changes do not. Using the formation (or lack of formation) of a new substance as the criterion for distinguishing between the two types of change seems straightforward. However, a pair of demonstrations made students aware that their current, limited understanding of chemistry reduced the usefulness of this criterion. Both involved color changes brought about by the addition of heat. The first involved placing a warm hand on a sheet of liquid crystals, which changes from a brownish-black to various shades of green and blue; the second involved heating cobalt (II) chloride hexahydrate in a test tube with a laboratory burner, producing a change from a wine color to a royal blue.

The first color change—of the liquid crystals—is an example of a physical change brought about by a shift in the alignment or orientation of molecules with respect to each other. The second—of the cobalt (II) chloride—is a chemical change brought on by the release of water from the hydrated form. The point made was that until students’ chemical understanding evolved, they would need to rely on macroscopic clues to indicate what type of change had occurred. Mr. Criswell then discussed signposts of chemical change that would be used throughout the course (i.e., dramatic energy change, color change, precipitate formation, formation of a gas, and production of an odor). These activities laid the groundwork for students engaging with models of phenomena, a critical part of classroom inquiry science.

**Model Testing**

Developing arguments based on evidence is an organizing principle in the National Science Education Standards’ essential features of classroom inquiry, which include questions, evidence, explanations, and justifications (NRC 2000). Windschitl (Chapter 1) suggests that argumentation in science is organized by “developing models and hypotheses and then testing them against evidence derived from observation and experiment” (p. 2). This does

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1 For example, product LC-2530A, available from Educational Innovations at www.teachersource.com
not mean having students debate different models by picking a side and defending it, as argumentation has often been misinterpreted, but is instead an empirical testing of alternative models.

For teachers to engage their students in model testing, multiple viable alternative models must be brought to the table for students to discuss and test against evidence. By drawing on the history of his discipline, specifically historical models of combustion, Mr. Criswell was able to frame his students’ investigations in a historical disagreement between competing models of combustion—phlogiston theory and Lavoisier’s theory.

Following the discussion of physical and chemical change, students were asked to set up an investigation: Weigh a piece of steel wool, rinse it with water, push the steel wool into the bottom of a test tube, invert the test tube in a beaker containing water, and adjust the water levels inside and outside the test tube until they are equal.

Over the next several days, students spent a few minutes of class time looking for and noting changes in this system. The most obvious changes were that the steel wool underwent a color change (as a result of rusting) and that the water level inside the test tube went up (as a result of removal of oxygen from the air). After a couple of days, the students were encouraged to propose hypotheses concerning the cause of these changes and then to design simple experimental variations to test these hypotheses. Many students speculated that rusting was somehow involved in the process; however, Mr. Criswell never confirmed this proposed explanation.

The underlying connection between the set of investigations was not clear to students at this point, but Mr. Criswell had laid the groundwork for both multiple explanations and resolution of the conflict. The initial discussion, demonstrations, and investigation involving rusting set up a pattern of introducing multiple threads of activity that were simultaneous and interconnected. These activity threads had different life spans, with some investigations taking a few moments and others being revisited multiple times over several weeks. Students were asked to continually revisit the models available to them, including their own model for combustion.

Simultaneous to their investigation of rusting, students were introduced to one of the fundamental questions facing chemistry in the 18th century: What happens to mass during a chemical change? Working in pairs, students were given three investigations in which they produced a chemical change and were asked to compare the masses before and after this change had occurred.
The first reaction involved the burning of steel wool: iron + oxygen → iron (III) oxide (rust). The second resulted in the formation of a precipitate, as well as the subsequent production of a gas: copper (II) chloride + sodium carbonate → copper (II) carbonate + sodium chloride. The third led to the release of gas: citric acid + sodium bicarbonate → sodium citrate + carbonic acid → sodium citrate + carbon dioxide + water.

All three of the reactions were designed to produce data that initially seemed to contradict Lavoisier’s law of conservation of mass, because they did not take into account a gas as either one of the reactants (in the first case) or a product (in the second and third cases).

After the students shared their results with each other, Mr. Criswell presented Lavoisier’s law. He noted that this law has been generally accepted (with some caveats) since Lavoisier introduced it in the late 1700s.

**Mr. Criswell:** So can we try and summarize what happened to the masses in all three of the investigations?

**Kevin:** Well, sometimes mass went up, sometimes it went down, and sometimes it stayed the same, so it’s not the same every time for every reaction.

**Mr. Criswell:** But we have the law of conservation of mass from Lavoisier that says that should not happen, so what is going on with our data?

**Emily:** Well, in ours we could see a gas bubbling off, so maybe the mass went down for us because we lost some with the gas.

**Mr. Criswell:** OK, so that is a possible explanation for why the mass went down, but what would make it go up? Group that did the burning steel wool, yours went up, right?

**Rosh:** Yes, but we are not sure why exactly.

The class’s data did not support the conclusion that mass is conserved. “What can account for this discrepancy?” Mr. Criswell asked. Students were then presented the challenge of redesigning their experiments to take these gases into account. This proposition is simple in the case of the reaction involving a precipitate and the one involving the production of a gas. The burning of the
steel wool is problematic, however, particularly because the result obtained is counterintuitive—the mass actually shows an increase. The following day Mr. Criswell brought the investigation with steel wool into the conversation about conservation of mass:

**Mr. Criswell:** You have been looking for changes in the test tubes for the last couple days. What have you observed?

**Emily:** The water in the tube went up.

**Rosh:** And the steel wool rusted.

**Mr. Criswell:** How do you know it rusted?

**Kevin:** It turned brown and got all crusty, you can see it on the tube.

**Mr. Criswell:** What is rust? I mean what is going on chemically when something rusts?

**Kevin:** Oxidation.

**Mr. Criswell:** OK, fine, that is a nice science word, but what does it mean? Think about the different parts of the word.

**Emily:** It has something to do with oxygen.

**Rosh:** It means combining with oxygen.

**Mr. Criswell:** Combining with oxygen? But where does the oxygen come from in the tube?

**Rosh:** It comes from the water. There is oxygen in water.

**Emily:** No, it is in the air. The oxygen is in the air and when it combines with the steel wool it gets used up, and that makes a vacuum and the water gets sucked up into the tube.

Once the connection had been made and Mr. Criswell had clarified some of the points about air pressure and why the water level rose in the tube, the students were left on their own to consider the implications for both the water level change in the test tube (with the rusting steel wool) and the mass increase when the steel wool was burned.
Synthesis

At this point in the curriculum, Mr. Criswell had a multitude of activity threads in the story of combustion open for students to consider and draw on. The students had encountered spontaneous human combustion, physical and chemical change, and conservation of mass. They had conducted investigations involving rusting steel wool, burning steel wool, precipitates, and the production of gases. Mr. Criswell had not attempted to resolve these threads into an overall pattern or model, yet the goal of this complexity was not confusion and lack of resolution. The goal was for students to remain perplexed (and thus engaged and inquiring) until they could bring all of this complexity to coherent synthesis—to combine all the empirical work they had done with conflicting explanations of the underlying phenomenon.

Resolution was provided not by Mr. Criswell directly, but by the students themselves as they brought evidence from their own empirical investigations to bear on the problem and deliver their own explanations of the ties between these investigations. This process of synthesis allowed students to connect their understandings about their investigations to the normative understandings of science. Students’ developing explanations were facilitated and scaffolded by Mr. Criswell, who provided a rationale for creating explanations, connecting to everyday explanations, and assessing and providing feedback to students (McNeill and Krajcik, this volume, p. 123). The catalyst for students’ synthesis in Mr. Criswell’s class was a flawed model of combustion, the phlogiston theory.

The students had now completed a number of empirical investigations around the ideas of oxidation and combustion. At this point Mr. Criswell introduced students to phlogiston theory.

**Mr. Criswell:** If we use the phlogiston theory as a model to describe what happens in your investigations, what does it tell us?

**Emily:** As the chemical change happens, the reaction, some mass is lost because phlogiston escapes.

**Mr. Criswell:** Is there any evidence you have that can’t be explained using this theory?

**Rosh:** Well, yes, in ours the mass went up when we burned the steel wool. It should go down when it burns, because phlogiston is being released, right?
Mr. Criswell: So how many of you are willing to accept phlogiston theory? [no students raise their hands] OK, but it is up to you to make an argument against it. Use the investigations and the data from the class, from both your group and your classmates, as you form your own explanation.

Mr. Criswell pointed out to students that the phlogistonists accounted for anomalous data of this nature by postulating that phlogiston could have negative mass. Phlogistonists’ defense of their ideas led to a discussion of the ad hoc modification of many theories in the history of science in order to allow them to explain anomalous data. To provide additional data for the students to consider, Mr. Criswell began the next day with a new investigation: a study of the preparation and properties of an unknown gas. Students were told that the gas was produced from a combination of hydrogen peroxide and potassium permanganate. Students were also told that the discoverer of the gas, Joseph Priestly, was a supporter of the phlogiston theory until his death. Students were to undertake the preparation of the gas (oxygen) on their own and study the reactions of this gas with several materials (a glowing splint, a candle, charcoal, sulfur, steel wool, and magnesium ribbon).

Because students were already familiar with oxygen from previous lab work in class, they quickly identified the mystery gas. Again, Mr. Criswell did not confirm this conjecture, but pressed students to consider carefully the implications for the various investigations preceding the mystery gas investigation. Students were asked to use their identification to make predictions concerning the products of the various reactions they studied during the experiment. All of these built the empirical foundation for the development of their own scientific model of burning and for the summative activity.

A few days later students were asked to use the scientific model of combustion they had been developing to explain how a candle burns. Initially, they expected this would be a relatively easy undertaking—until they realized how difficult it was to isolate what was actually burning in the candle (the wax? the wick? something soaked into the wick?). Students soon found it necessary to design their own experiments to try to parse out the role of each of the parts of the candle.

Students were given two days to gather their data and observations and develop their explanation pertaining to the question of how a candle burns. During that time, Mr. Criswell acted as expert colleague and circulated around the room, pressing students on the interpretations they were making from the experiments being conducted.
Mr. Criswell: I don't really see how your explanation is taking into account the mass increasing when the steel wool was burned. Can you tell me how that fits in?

Kevin: Well, that data was from another group, so I didn't really think about it. I thought we just had to explain what our group found.

Mr. Criswell: Sorry, you have to take everyone's data into account. And you also have to make sure that when you say something like “for something to burn oxygen must be present,” as you said here, that you give evidence from the experiments we did in class. You have to make sure you can back up your claims with evidence.

Mr. Criswell also reminded students that no knowledge claim could be included in their explanation that did not have empirical support from their own experimental results. With the last portion of the time allotted for this investigation, students were asked to synthesize their results into a formal report.

Student reports were collected and a grand debriefing session was held, in which all of the activity threads from the past weeks were brought together. Mr. Criswell presented a model of burning known as the Triangle of Fire (fuel, oxygen, and heat). Students discussed how this model explains the process of a candle burning. The scientific explanation (with the wax as the fuel) was presented and compared to the conclusions students reached. Viable rationales for reaching alternative conclusions were considered. Mr. Criswell focused students' attention on the validity of their logic, as opposed to achieving some predetermined correct answer.

The Triangle of Fire model was compared to phlogiston theory. Specifically, phlogiston theory can explain how a candle burns, but it cannot explain the result obtained in the oxygen preparation experiment (in which a candle burned in pure oxygen maintained its flame much longer than one burned in air). Finally, the scientific explanation of how a candle burns was used to propose an analogous scientific explanation of how human combustion can occur (known as the “wick effect”). Mr. Criswell concluded the discussion by showing the students the last part of the spontaneous human combustion video, which presents experimental evidence for the wick effect explanation.
Conclusion

Mr. Criswell’s classroom exemplifies three key elements of inquiry science pedagogy: perplexity, model testing, and synthesis. Students engaged in multiple activities over many weeks with activity threads from different investigations coming to resolution and then being revisited in the context of larger themes and patterns. The classroom community was asked to generate multiple explanations for individual investigations, as well as test models, that explain multiple phenomena, and all tests had to be grounded in students’ own empirical investigations. Mr. Criswell did not dispense correct answers, and answers were not the primary goal of the students’ work. The synthesis in which students were engaged had a clear set of criteria for choosing a model or theory. The model had to be empirically adequate, had to explain a range of phenomena, and could not be ad hoc. The only synthesis Mr. Criswell accepted from students was a thoughtful and empirically supported explanation that could encompass multiple, seemingly conflicting pieces of data from a number of different phenomena—exactly the goal of any scientific theory. By creating an environment of sustained yet evolving scientific perplexity, Mr. Criswell could support his students in doing the hard thinking—the supposing and critiquing. Although these students were not creating new knowledge for an external audience, they were engaged in scientific discovery, model testing, and theory building.

One of the most interesting things about this sequence of activities from Mr. Criswell’s room was the degree to which it was both teacher directed and exemplary inquiry science pedagogy. Much of the literature on inquiry science argues explicitly, implicitly, or in the form of levels of inquiry (e.g., Schwab 1962) that student-directed inquiry is of a higher order or value than more teacher-directed versions. However, the example of Mr. Criswell’s chemistry class shows that by careful, long-range planning a teacher can provide opportunities for students to engage in inquiry activities that provide greater insight into the history, content, and nature of science than a more open version of inquiry might. It is further evidence that we educators need to look beyond a single idealized version of classroom science inquiry and begin to understand the elements of inquiry pedagogy that make it a powerful instructional approach.