Chapter 1

Rethinking How Science Is Taught

WHAT SHOULD BE OUR GOAL in the teaching of science? Lynn Margulis, a world-renowned microbiologist who is the former president of Sigma Xi (a highly respected organization of research scientists), wrote the following in her ''President's Message'' column in the November-December 2005 issue of *American Scientist* (a journal of Sigma Xi): ''Francis Bacon, who some consider to be the father of modern western science, wrote over 350 years ago, 'for what a man more likes to be true he more readily believes.' '' She stated in her column that, ''We scientific researchers resist this natural tendency. We do not try (only) to be true. We discount gossip. We disdain common myth. We seek hard evidence. And when doing science, we try to avoid the influence of faith-based dogma. *Yet all of us who participate in science share one common faith. We believe that the material energetic world is knowable, in large part, through the concerted activity of research, exploration, reconnaissance, observation, logic and detailed study that includes careful measurement against standards* (italics added).''

Margulis goes on to state that, ''supposedly we are the richest and freest country in the world. Then why do 15 year old U.S. students rank 22nd of 40 countries in science literacy, according to the latest survey conducted by the Organization of Economic Cooperation and Development (OECD)?'' She concludes that ''this condition may result (for the most part) from a contradiction in our national psyche, a deep cultural divide in that truths are (too) often sacrificed to what most people like to be true and thus more readily believe.''

Critical Thinking and Inquiry

The messages of Francis Bacon and Lynn Margulis have particular relevance to us as science teachers and as authors of this book. That is because we have a special responsibility to set as one of our teaching goals the preparation of ourselves and our students to overcome the ''natural'' tendency to believe as fact that which we like and to discard that which we do not like even though it has been proven. We as teachers of science overcome this tendency first by inquiring about our own understandings and then by expecting our students to do more than listen and memorize factual information. Rather, it is our responsibility, through schooling, to prepare (even train) students to inquire into their own understandings and thus to become educated to think in the way that scientists do. Although it is important for students to understand the content of science, it is equally essential that they learn about the purpose and methods of science (this can be called the ''scientific enterprise''). This means that we must expect our students to develop habits of mind and critical reasoning skills that enable them to participate effectively in the scientific process: to grapple with scientific problems, to question conventional wisdom, and to be able to seek out hard evidence in support of their arguments. A recipient of the Nobel Prize in physics, Sir William Henry Bragg, stated it this way: ''The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them.''

In the past decade, numerous publications have called for ''inquiry'' approaches to science instruction that can effectively help students develop critical reasoning capacities, including the ability of students to pose scientific questions and investigate them, to accurately record and interpret the results, and to be able to link their findings to a developing body of scientific knowledge. The most significant of these publications is *Inquiry and the National Science Education Standards*: *A Guide for Teaching and Learning* (National Research Council, 2000). This document provides detailed standards along with guidelines for introducing inquiry as both an experiential process and the goal to be met through K–12 science instruction. (The specific standards for grades 6–12 learning will be addressed in later chapters.) In a more recent report, *Taking Science to School: Learning and Teaching Science in Grades K–8* (National Research Council, 2007), the National Research Council (NRC) continues its emphasis on science instruction that directly engages students in the *practice* of science, citing the following four proficiencies to be developed for all students in grades K–8:

1. To know, use, and interpret scientific explanations of the natural world.
2. To be able to generate and evaluate scientific evidence.
3. To understand the nature and development of scientific knowledge.
4. To participate productively in scientific practices and discourse.

The NRC report indicates that ‘‘these strands of proficiencies in addition to representing learning goals for students as well, need to serve as a broad framework for curriculum design.’’

Understanding Student Inquiry/Discovery

Although much has been written on the topic of inquiry, understanding it, especially as it applies to instruction, has proven to be challenging to many science teachers. This is because the term has been used with different meanings when applied to education. The NRC, in *Inquiry and the National Science Education Standards*, has its own definition, and in addition, many states have their own particular definitions as expressed in their science education standards. We will take up the specific NRC ‘‘inquiry standards’’ a bit later in this book, but here’s a basic description for *inquiry* included in the Standards document as applied to instruction: ‘‘When engaging in inquiry, students describe objects and events, ask questions, construct explanations, judge these explanations against current scientific knowledge and communicate their ideas to others.’’

The instructional framework proposed throughout this book is based on a simplified and clearer understanding of inquiry, especially in reference to the role of students. Most English-language dictionaries associate *inquiry* with the verb ‘‘to inquire,’’ which is defined in *Webster’s Collegiate Dictionary* as ‘‘To ask about, to put to question or to seek information by questioning.’’ This definition has naturally led some to the conclusion that inquiry simply is the single skill of asking questions. In instruction, the important distinction is that the inquiry process can be either student-directed or teacher-directed. A major goal of our instructional process should be to encourage students to take the initiative in posing the questions or inquiries.

You have probably noted that young children begin to inquire using the word *why* (‘‘Why is the sky blue?’’ for example). Parents attempt to answer such questions, not always successfully. Nevertheless, children continue to ask these kinds of questions often well into the early grades. In the later grades, however, students become less inquisitive and, as teachers too often have observed, rarely ask questions except those that relate to instructional procedures or to the grades they have received. Instead they appear to sit and absorb knowledge like little sponges, until tested, when they reveal they have absorbed very little, unlike sponges. A major reason for this is that they have become ‘‘tuned in’’ to the idea that it is a major role of teachers to ask them questions. Therefore, they have ‘‘tuned out’’ any queries they might have to areas of confusion, being satisfied (at least on the surface) with ‘‘covering’’ the material under study.

In the inquiry/discovery approach, teachers are encouraged to restructure their presentations to reduce lecturing and asking their students questions and instead, to open the door for students to do the inquiring, with the teacher providing guidance and encouragement, at least until students return to what was once a natural and useful habit. Eventually, with such guidance, students will inquire profusely, even asking questions that are of higher order: questions that, for example, begin with words such as *how*, *which*, and *why* (the inferential), rather than simply *who*, *what*, *when*, and *where* (the observable). Inquiry-oriented instruction enables students to practice and develop the particular skill of asking higher-order questions that are relevant to the area under study.

We now turn to an understanding of *discovery* related to its use in instruction. According to the *American Heritage Dictionary*, *discovery* is defined as ''the act or instance of discovering or of something discovered through those actions.'' Notice that the term is used as both a verb (a word of action) and as a noun (a label for the results of the action). We follow this dual usage as well when we state discovery is the investigative process that students undertake in response to inquiries (preferably their own inquiries), including the findings and outcomes of that process. Unlike student inquiry, which involves only one skill (effective questioning), the process of student discovery involves the development of many investigative skills. In science, for example, the critical skills include observing, reasoning, measuring, mathematical manipulation of data, preparation of tables and graphs, and interpretation of data, all used in the processes of explaining and developing valid conclusions. Other skills, too often not historically associated with science instruction, that are not emphasized include the following: virtually all language skills (reading, writing, speaking); wondering; explaining; editing; revising; discussing; thinking; and analyzing. Thus we conclude that inquiry and discovery-oriented instruction enables students to develop and practice many investigative skills in the search for answers to their own inquiries. Students, in effect, become researchers. Of course, as students pass from one grade to the next, the necessary resources that they seek in the practice of discovering must be attainable or students will, once again, stop inquiring and discovering.

Although student inquiry and student discovery are distinctly different, as we have just described them, they are in fact closely intertwined. Many professional educators have referred to the combination of the two simply as ''inquiry.'' We prefer the term *student inquiry/discovery*, because it helps to remind us, as teachers, to increase the involvement of our students in both processes symbiotically. Therefore we continue to emphasize the combined terms throughout this book.

Teaching Strategies for Inquiry/Discovery Learning

In his foreword to the NRC Standards book (2000) mentioned earlier, Bruce Alberts, president emeritus of the National Academy of Science, refers to *inquiry* as a ''state of mind.'' Although it is true that inquiry requires new ways of thinking, developing these habits of mind, especially through hands-on experiences, is not yet standard practice in many science classrooms. In part, this is because teachers lack guidance in designing investigations in ways that facilitate students' practicing and learning to inquire and think critically about evidence and then to discover. Our goal in this book is to show how the inquiry/discovery process not only enlivens lessons based on or driven by laboratory investigations, but also builds deeper understandings of science content. This instructional approach offers a framework for structuring lessons so that students can and will become more deeply engaged and take greater interest in their learning.

Before introducing our lesson-planning framework in Chapter Two, we here portray two different ways of teaching a science lesson: (A) a didactic or teacher-centered approach, and (B) an inquiry/discovery-oriented approach. Both lessons focus on the concept of ''force and motion'' for the middle school level.

Lesson A: Force and Motion (Conventional Approach)

Student Learning Objectives:

- To correctly define the terms *force*, *motion*, *speed*, *velocity*, *acceleration*, and *inertia*
- To be able to solve mathematical problems that involve these terms and thus to understand their meanings and how they relate to one another

We enter the classroom of a middle school teacher of science, where the teacher is asking students to review the definitions of the terms *force*, *motion*, *speed*, *velocity*, *acceleration*, and *inertia*, which he had presented on the previous day. When students are asked to give examples, several refer to the assigned reading from the night before. Some students are unable to answer the question, having not read or understood the assignment. The teacher uses that opportunity to introduce the objective and procedures for today's lesson. Students open their textbooks, and individuals answer questions posed by the teacher from the reading. The teacher then uses the book material to introduce the mathematical formulas pertaining to force and motion, as well as velocity and acceleration. He then demonstrates on the chalkboard the use of a ''plug-in'' technique for calculating answers to those problems, based on the set formula. Meanwhile, the students watch him and copy the solutions. The teacher then assigns the students to use the same procedures to solve the next four problems at the end of the chapter. He moves around the room as they work, checking their procedures. For homework, students are asked to complete the remainder of the textbook problems independently. The students are given the timetable for completing the unit: a review the next day, a test on the problems the following day, and a final review of the material when the teacher returns the tests the following week. The plan for this sequence of lessons is as follows:

Lesson Plan (Force and Motion):

- The teacher will describe and define the terms *force*, *motion*, *speed*, *velocity*, *acceleration*, and *inertia*.
- Students will read the chapter, and the next day the teacher will introduce it by asking them to answer questions about content from it.
- Before the end of the period, the teacher will solve four sample mathematical problems related to force and motion: numbers 1 through 4 at the end of the chapter (day 1).
- Students will solve problems 5 through 12 at the end of the chapter for homework, and the teacher will review these during the next period (day 2).
- A test on definitions and solving plug-in problems will be given (day 3).
- Eight days later, the teacher will review problems that were solved incorrectly on the test and will correct definitions, orally.

Comments on Lesson A (Conventional Approach)

According to the lesson plan, most of the instructional activity is the responsibility of the teacher. The students are only given responsibility to read the chapter ''Force and Motion'' and to solve mathematical problems, and be prepared to answer questions asked by the teacher about the content. The activity consists of having individual students respond orally to the teacher's questions about the material ''covered'' and then follow the teacher's directions in completing the problems. Experience indicates that students do not usually respond well, if at all, to such teacher-generated questions, for several reasons: students have not read the assignment, they have read the assignment but do not understand it, or the teacher does not offer each student called on enough time to think about and respond effectively to the questions asked. Very often the teacher ends up answering each question him- or herself. Teachers often attribute this poor student response to the students' unwillingness or inability to read the text. Either way, students often are unable to effectively interpret the meaning of the content. Rather than addressing the causative factors that produce this outcome by modifying their instructional strategy, teachers continue to repeat the unsuccessful instructional approach over and over, especially in providing both the questions and the answers. This particular approach to learning encourages students to be ''nonparticipants'' in their own education. The result is apathy to the assignment and, ultimately, to the subject matter itself. This form of instruction, often referred to as the traditional or didactic approach, not only places an increased instructional burden on teachers, it also leads to lower morale for both teachers and students, resulting in a lowered efficiency of learning. It is truly teacher-centered and, as indicated, it is very ineffective in enhancing students' understanding of scientific content and in developing their interest in science as a field of study.

Lesson B: Force and Motion (Inquiry/Discovery Approach)

We approach the classroom of another middle school science teacher, Miss Biggs, teaching the same material. To convey the classroom dynamics, the lesson is presented in a narrative form. The student learning objectives are briefly noted below, but as you will note, the objectives are not revealed to the students until the lesson evolves.

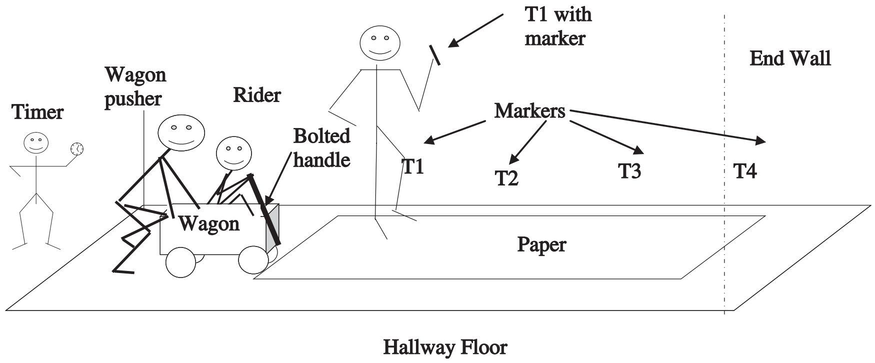
Student Learning Objectives:

- To understand the meaning of force and motion, and how the terms *speed*, *velocity*, and *acceleration* are related to these
- To learn how to solve mathematical problems associated with force and motion and how the mathematics formulas correlate
- To develop skills in posing questions, preparing graphs, analyzing data, and summarizing content knowledge

This sixth-grade teacher begins this sequence of lessons on force and motion by indicating to her students that for the next few days they will be exploring the characteristics of a moving wagon and the distance it can travel, over time (four seconds). This period of time enables an investigation to be carried out safely in a school hallway. The teacher's instructions to the students are as follows: ''First, let's look at the materials we will use. They include a wagon with the bolt at the base of the handle tightened so that the wagon will only be able to move in a straight line. In addition, we will use a long strip of wrapping paper about eight meters in length, a meter stick (with both English and metric units), masking tape, Magic Markers, scissors, bathroom-type scales, several physical science textbooks,

FIGURE 1.1

Investigating Force and Motion.



and historical references.'' The teacher points out that all of these items will be important tools for students to use as science investigators.

She divides the class of thirty students into seven teams of about four each, with each team including students of varied levels of proficiency. Each member of each group is eventually assigned to carry out one of the activities that make up the investigation. Each student is given a copy of the printed directions for carrying out the procedure that includes a diagram (Figure 1.1). One student from each group is called on to read the procedure out loud to the rest of his or her group. Each group is invited to ask the teacher any questions about the procedure. Only two questions are asked: ''Who will ride in the wagon?'' and ''Who will push the wagon?'' The answer is automatic; two students volunteer, accompanied by considerable laughter and joviality.

The class gathers in the hallway, which serves as the ''informal'' science laboratory. One student notices that the hall is carpeted, unlike the classroom, where the wagon would move more easily. She asks if that is important. The teacher responds first by congratulating the student on her excellent observation. She then asks the student to write the question on the chalkboard when the class returns to the classroom and further comments that, once the initial investigation is completed, the class will return to this question and other questions during a follow-up investigation.

Two students from Group A are assigned to follow the directions indicated by the diagram (Figure 1.1) and to tape the wrapping paper along the hallway floor. To ensure safety, the teacher makes certain they provide enough distance between the far end of the paper strip and the end of the hallway to allow the wagon to complete its approximately four-second journey without crashing into the wall. Another two members from Group A align the front wheels of the wagon along the outside edge of the paper strip. With great fanfare, the two volunteers, one to ride, the other to push, take their positions. First there is a trial run. A student from Group B volunteers to be the starter and practices counting, ''3, 2, 1, go!'' A second student from this group volunteers to be the timer. Using a stopwatch, she practices counting each second, ''1-1,000, 2-1,000, and so on'' that the wagon moves. (No stopwatch is actually required, because counting ''1-1,000, 2-1,000, and so on'' is a consistent measure of time.) Students in Group C squat in various positions along the side of the paper strip nearest to the wall, and with Magic Markers in hand, mark the point where the front wheels of the wagon are in line on the paper strip at the end of each second counted.

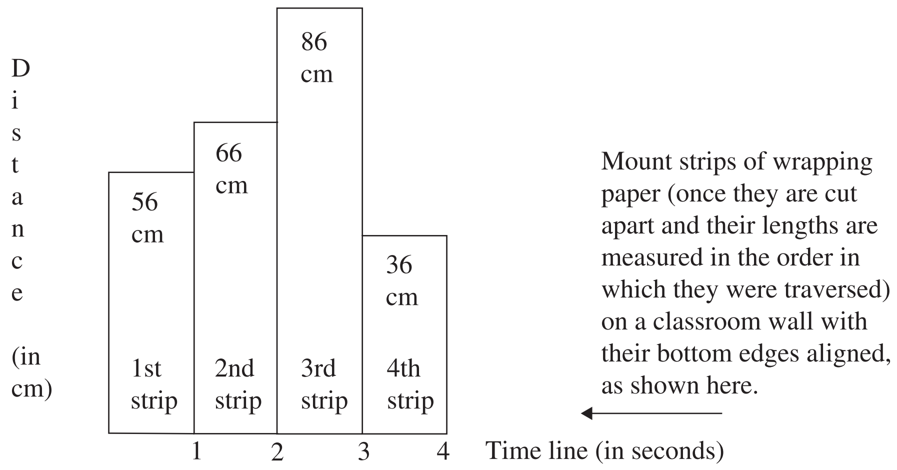
Following the trial run, the student who volunteered to ride in the wagon is weighed, and this is recorded for future reference. Then the investigation officially starts. As soon as the wagon begins moving, the Group C students mark on the paper the distance traveled each second for the total of four seconds. Group D students use the markers to consecutively number each section of the paper strip and then cut across the strip at each mark, producing four segments total. Following the cutting, each segment is measured and its length recorded on the strip, marking the distance the wagon traveled during each second of time.

Returning to the classroom, Group E students mount the segments of paper consecutively onto the wall, with the bottom edges resting horizontally on the floor (Figure 1.2). The teacher then calls on Group F students to describe, verbally, what the length of each strip of paper represents and to indicate why the directions called for placing the strips next to each other in this way. With the teacher's support, the students eventually recognize that the paper strips provide visual representation or a ''bar graph'' of the wagon on its journey. They are asked to label the horizontal and vertical axes of this incomplete graph. The students then discuss the length of each segment, noting with some controversy that some segments were measured in metric units (centimeters) and others in English units (inches). The teacher encourages them to consult a handbook that is available in order to convert all the measurements to one system of measurement.

For the final activity of the instructional period, the teacher invites the students to observe the bar graph and to draw it in their notebooks as a record of the collected data. She then asks students to think about what they have observed and to develop within each group questions that need to be answered and points that need clarification. In formulating their questions, the teacher requests that the students include at least four questions

FIGURE 1.2

Visualizing Measured Distances Traveled by a Pushed Wagon During Each Second of Time.



that involve numbers. The example given was, How far did the wagon travel during the four seconds? They also were to include certain terms (*inertia*, *force*, *motion*, *speed*, *velocity*, and *acceleration*) in their questions. She encourages the students to consult the textbook chapter on force and motion or other available references to help them clarify each definition. At the end of the period, the questions developed by the student teams were presented to the class and then consolidated and sequenced for follow-up discussion the next day. Some of the questions raised by the student teams were

- Why did the wagon move farther during some seconds than during others?
- What caused the wagon to speed up? To stop moving?
- Where does the energy come from to cause the wagon to move?
- Would the data be the same if there was no friction between the wagon wheels and the floor? Suppose the floor had not been carpeted? Suppose there was a heavier (or lighter) student in the wagon?
- What if the wagon had been allowed to roll down a hill? What if it were pushed up a hill? How would this data look on a graph?
- How far did the wagon travel or move during the first three seconds?
- How much slower did the wagon travel during the fourth second compared to the third second? Why?

- What was the average speed (or is it velocity) of the wagon over the four seconds? How do speed and velocity differ?
- How much farther did the wagon travel during the second second than during the first second?

The teacher then reviewed the day's activity with the students, reminding them that they were to be prepared the next day to answer the questions that they generated. The teacher pointed out or reminded them that some of their answers must be mathematical, and that the students should carefully think about the relationships among the terms used in the questions, referring as necessary to the textbook chapter.

The next day the teacher invited students to present their answers and explanations regarding the questions posed the previous day. She also discussed the use of mathematical formulas as a means of finding answers using data collected by others. The teacher concluded the session by informing students that the ''test'' related to this investigation will be a letter that each student writes to a friend, explaining what the class did, the conclusions they have come to, and what they had learned. She reminded them that like any good narrative, the letter needs to include clear statements of events as they occurred as well as explanations of what was learned throughout this activity. Also, the test will call on each student to design three mathematical problems related to the data they collected and to solve each problem correctly. Each student also is to design a parallel problem using a car or an airplane in place of the wagon. All problems are to be solved and the answers clearly stated. Following is an example of a letter written by one of the students to a friend in which she describes the activity and the results that were obtained.

October 2, 2008

Dear Jose,

In our science class over the last few days, our teacher, Ms. Biggs, had us conduct an experiment in which we analyzed what happened when a wagon was pushed down the hall, outside of our classroom. This was fun because we saw Bill ride in the wagon. Everyone wanted to have a turn. We measured how far the wagon moved each second over four seconds, after Mary used enough force to overcome the wagon's inertia. We placed a paper strip on the hallway floor and marked on it where the moving wagon was at the end of each second. Then we measured these distances and marked the measured distances on the paper strips and cut the strips.

Then we went back into our classroom and taped the strips on a wall to make a bar graph. Our teacher asked us to write questions about the moving wagon that involved the data we collected. Here are examples of questions that I wrote:

- How far did the wagon move during the first two seconds?
- How much farther did it move during the second second than during the first second?
- What was the average speed of the wagon over the four seconds?
- What percentage of the total distance did the wagon move during each second?
- How accurate were our measurements?

To answer our questions we looked up in our science book the meanings of words like force, motion, inertia, friction, speed, acceleration. Our teacher helped us to use these words in studying the graph. Oh, I almost forgot to say that one team measured the distance the wagon moved in feet while the other three groups used centimeters. This meant that we had to find out how to convert all of the distances to the same unit of measure.

This was a fun lesson. We gave the graph a title: ''The Moving Little Red Wagon!'' Our teacher told us that we would have an opportunity to apply what we learned to other examples such as a moving car. I'm working on this problem now. Hope your science classes are as much fun and you learn as much as we do!

Sincerely,
Mary Ellen

Comments on Lesson B (Inquiry/Discovery Approach)

The letter indicates that the students' involvement made the science learning more palatable than if the content had been presented using the usual didactic approach. In addition, students gained experience in applying mathematics skills to science and in searching for information rather than simply listening to the teacher present the information. Of course, learning does not fully develop from a single experience like that described in the preceding case history. However, the approach results in students wanting to learn more. Perhaps even more significant is that the instructional approach emphasized here results in students becoming engaged in a hands-on investigative experience; the approach will also encourage students to pose their own questions, to experience gathering evidence (data), and to gain experience in discovering or developing conclusions. There are many additional aspects of science teaching that are addressed more extensively throughout this book.

As we shall see in the next chapter, it is possible to obtain significant improvement in students' scientific thinking skills through a better understanding of the true nature of ''reformed'' instruction. Thus you can be assured that by emphasizing certain teaching strategies and procedures in instruction, as described in later chapters, not only will you be able to address the objectives and goals that are so crucial to the nation's future well being, but most immediately important, your students will gradually meet these objectives and goals.