Teaching Earth Science Through Inquiry

TOILET PAPER TIMELINE

In this case study, we will observe Tom O’Brien, an associate professor of Graduate K–12 Science Teacher Education at Binghamton University in Binghamton, New York, lead an earth science class through an investigation of constructing a toilet paper timeline and geologic scale while using Internet resources for researching topics in geologic history and fossil formation. This case study, although fictitious, is based on O’Brien’s article “A Toilet Paper Timeline of Evolution” (2000).

A researcher in inquiry-based instruction and constructivist teaching strategies, Tom has years of experience with National Science Foundation (NSF) grants focusing on teachers implementing the 5E Learning Cycle. Prior to teaching at Binghamton, Tom was a high school chemistry teacher in Kentucky and one of the original contributors to Chemistry in the Community (known as ChemCom), an interactive, community-based high school chemistry program.

The “Toilet Paper Timeline” inquiry aligns to the National Science Education Standards (NRC, 1996) for grades 9–12, which are quoted below.

Science as Inquiry Standard

Students will

- Formulate and revise scientific models using logic and evidence. (p. 175)
- Recognize and analyze alternative explanations and models. (p. 175)

Life Science Standard

- The great diversity of organisms is the result of more than 3.5 billion years of evolution that has filled every available niche with life forms. (p. 185)
Earth and Space Science Standard

- Observing rock sequences and using fossils to correlate the sequences at various locations can estimate geologic time. (p. 189)
- Evidence of one-celled forms of life—the bacteria—extends back more than 3.5 billion years. (p. 190)

Introduction to the Lesson

The historical perspective of time, as it relates to the geologic past, creates an intriguing scientific lesson. A change in the age of the planet Earth, from a few thousand years to hundred of millions, first proposed in the early 1800s by Charles Lyell, created a major paradigm shift in the minds of many believers and nonbelievers. This newly proposed model was “based upon indirect evidence from fossils and rock formations and supported the even less acceptable concept of biological evolution” (AAAS, 1993, p. 246). Nearly 200 years later, biblical literalists still challenge the scientific perspective on the age of Earth. The notion of time and scale provides students with an engaging vehicle for understanding how models and theories come to be accepted within the science community.

The concept of scale as a unifying theme is not new to most students. Since their earliest years, children have experienced scale models of cars, trucks, planes, trains, dolls, and other toys. Children know that the toy model they hold in their hands represents a smaller version of the original. The reality of scale seems to make sense. Even as elementary school students learn to read maps, they begin to understand the significance of scale. Often maps include a scale key (for example, 1 inch = 1 mile) to show the relationship between the illustration and reality. Today’s high school students, however, are faced with understanding scientific scales ranging from hundred of billions to the microscale concept of a nanometer.

When studying the cosmos, earth science students need to comprehend the immensity of a billion. When studying our sun, we find it is just an average star in size, brightness, and age among 100 billion other stars in the Milky Way galaxy. The concept of a billion also arises when we consider the population explosion of Earth. With the population reaching 6 billion in 2000 and rising each year, some scientists predict that Earth can support only between 10 billion and 15 billion inhabitants. Thus, whether it is vast numbers of bodies in the universe or the population of humans on Earth, the notions of time, scale, and using models become important scientific themes for high school students.

According to the National Science Education Standards:

in studying the evolution of the earth system over geologic time, students develop a deeper understanding of the evidence... of the Earth’s past and unravel the interconnected story of earth’s dynamic crust, fluctuating climate, and evolving life forms.... They will discover that while certain properties of the earth system may fluctuate on short and long time scales, the earth system will generally stay within a certain narrow range of millions of years.... Many students are capable of doing this kind of thinking, but as many as half will need concrete examples and considerable help in following multi-step logic necessary to develop the understanding described in this
standard. Because direct experimentation is usually not possible for many concepts associated with earth and space science, it is important to maintain the spirit of inquiry by focusing the teaching on questions that can be answered using observational data, the knowledge base of science, and processes of reasoning. (NRC, 1996, pp. 188-189)

The evolution of the earth system, including both geological and biological factors, is more challenging for students to understand because of a number of conceptual, methodological, philosophical, and secular factors. One of the most difficult issues for high school students is geologic time, partly because we have difficulty fathoming numbers larger than a thousand, much less a million or a billion. Textbooks also contribute to this problem by showing a timeline with squiggly or broken lines for an era too large to fit on one page. Unfortunately, truncated scales are a necessary evil given the size dimensions of a textbook. Teachers, however, do not have to be limited to the scale drawing from textbooks. They can provide alternative and authentic performance tasks for students to help them grasp the reality of time, scale, and models. The following case study shows how one college professor presents a series of lessons to a high school earth science class and wipes away misconceptions about geologic scale. The lessons came about when Tom was discussing with his graduate-level science education students the 5E Learning Cycle. Toward the end of the class, Joanna Moore, a student in Tom’s course, came up to him and asked if he would be interested in teaching a class for her 11th-grade earth science students at Thomas Edison High School. He agreed, thinking that he’d design the lessons to introduce students to the scale age of Earth while modeling for Joanna the 5E Learning Cycle. The “Toilet Paper Timeline” is presented in five separate lessons spanning several days. He uses the Engagement stage to introduce the concept of a scale and models, the Exploration stage to make the timeline, and the Elaboration stage to extend the lesson into an inquiry-based investigation. Arrangements were made, and 2 weeks later Joanna’s college professor found himself facing a class of eager young minds in Room 214 at Edison High.

Engagement

“Let’s begin by thinking and reflecting what we know about the age of Earth,” Tom begins. “How old is Earth?” he asks the class while writing the question on the board. “Is it 10,000, 500 million, 1 billion, or 4.6 billion years old? Make an estimate as to the age of Earth and write that number down on a sheet of paper.” He then asks the students to pair and share their estimate with someone sitting next to them and give a reason why they chose the number they did. As the students work in pairs, Tom and Joanna circulate about the room, listening to the comments being made and mentally noting possible misconceptions. Of the 24 students, 11 choose 4.6 billion years, 6 choose 1 billion, 5 choose 500 million, and 2 choose 10,000 years. After recording the estimates on the board, Tom asks several students to provide a rationale for their answers. One student, Lisa, responds by saying she read in a magazine that Earth is more than 4 billion years old, so that seemed like the best answer. Rather than giving the class an immediate answer, Tom probes further by asking, “How do scientists estimate the age of Earth?” A discussion develops in which students receive a brief background on radiometric dating. Students later are told
that, based on scientific testing, geologists now date Earth’s origin to be 4.6 billion years ago.

“How can we understand such a large number? How much is a million? Or a billion?” Tom asks. “To understand the concept of a million, look at this jar.” Holding up a 1-gallon glass jar, he says, “It contains 1,000 jellybeans. Now, how many jars would we need to represent a million jellybeans? How about a billion jellybeans? Figure it out and tell Ms. Moore and me your answer.” The professor also challenges students to come up with other representations of a million or billion and poses the question, “Suppose you wanted to put 4.6 billion jellybeans in this classroom. Is it possible? How much room would 4.6 billion jellybeans take up?” By the end of the first half hour, students are beginning to construct a concrete understanding of the concepts of a million and a billion. Tom concludes this portion of the lesson by saying, “Now it is time to move on and design a geologic timeline.”

**Exploration**

“Open your earth science textbook to page 205. What do you see? That’s right, it’s a geologic timeline. But is the timeline drawn to scale?” Tom asks. “No,” he answers, after a brief pause. “You can see that all the eras are pictured equally in size; however, the time spans of all the eras are not equal. Suppose we use this meter stick for the entire age of Earth. The combination of the pre-Archean (pre-Cambrian), the Archean (Cambrian), and the Proterozoic eras,” he says while holding up the meter stick, “would extend from the beginning of the meter stick to 89 cm, the Paleozoic era would extend from 89 to 95 cm, the Mesozoic era from 95 to 99 cm, and the Cenozoic era would be in the last centimeter of the meter stick. So you can see that all the eras are not equal in length of time.”

“In this 2-day investigation, each group will create a geologic timeline drawn to scale. To do this, you will use a roll of toilet paper to represent time and determine what data and information you need to complete the timeline. Knowing Earth’s history is actually 4.6 billion years old, read the outer wrapper to determine the number of sheets a roll of toilet paper contains. Then you will have to mathematically calculate how many years each square sheet represents.” For information about the age of Earth, relative geologic timelines, and major divisions in geologic time, Tom directs students to the U.S. Geological Survey’s Web site, http://pubs.usgs.gov/gip/geotime.

As students begin their investigation, Tom places several different brands of toilet paper on the front table. Students now decide which brand to use for their timeline. Some brands are single-ply, others are two-ply. Some are smooth, and some are quilted, with an imprinted design. Some are plain, and others are scented. Cottonelle contains 264 two-ply sheets, and other brands contain 170 or 300 sheets. Both Charmin and Quilted Northern have 400 two-ply sheets, while Scott has 1,000 single-ply sheets on a roll.

Some students ask if they can manipulate the number of sheets used in the timeline to represent Earth’s 4.6 billion years. One group wants to round off the number of sheets used to 230, figuring that number can be divided easily into 460, making each sheet equal to 20 million years. Another group wants to increase the number of sheets it uses to 460, making each sheet equal to 10 million years.
Once the time span is determined, students then identify sheets on the timeline for each of the four eras. Some students choose to use colored markers to distinguish among the four eras. Students also identify specific sheets to represent when life begins, the rise of marine invertebrates, the development of flowering plants, the age of dinosaurs, and the time when humans first appeared on Earth. Upon completion, the groups carefully post their toilet paper timelines, ranging from 40 to 80 feet, on the hallway and cafeteria walls, with Tom and Joanna Moore leading a discussion comparing and contrasting the different models. The discussion guides the class into the next phase of the lesson: the Explanation.

Explanation

By the fourth day, students develop a good understanding of the unifying themes of scale and models. Tom begins this day’s lesson by saying, “It is now time to provide some background information to our timelines.” By using simulations, discussions, videos, and virtual Internet field trips, he presents a lesson that focuses on fossil evidence for the appearance of various life forms on Earth and the stories that fossils tell us. As a homework assignment, students are directed to the U.S. Geological Survey Web site for research on index fossils (http://pubs.usgs.gov/gip/geotime) and for fossil formation and succession information (http://pubs.usgs.gov/gip/fossils/).

The second part of the Explanation stage centers on scientific notation. According to Tretter and Jones (2003), “in order for students to appreciate the vast differences in size of various biological or physical systems, they need a firm grasp of scientific notation” (p. 23). The presentation on the age of Earth now evolves into
a lesson on scientific notation and its application to geology, space science, biology, chemistry, and physics. To complement the discussion, students view a Web site, www.wordwizz.com, based on the 1970s film *The Power of 10*. At this site, which integrates space science with biology and chemistry, students observe images from the subatomic quark \((10^{-16} \text{ m})\) to the galactic quasar \((10^{25} \text{ m})\).

**Extension/Elaboration**

On the fifth and final day, students critically evaluate other scales and timelines in their science textbook. Students determine if they are to scale, and if not, how they can be revised to represent an accurate scale. Several students bring up additional illustrations in other chapters of the book that inaccurately illustrate the relative sizes of Earth and the Moon. These students discuss and analyze the actual size and distance relationship between the two bodies. Other students find similar illustrations showing the solar system or universe out of scale because of the size limitations of the textbook page.

To provide more details to their geologic timeline, students are given a take-home assignment. During this Extension/Elaboration stage, students can choose any topic to investigate that applies to their timeline. Tom and Joanna provide suggestions, including the following:

- For any one of the geologic eras—Paleozoic, Mesozoic, or Cenozoic—choose one plant or animal fossil and research its geologic record. Place the fossil accurately on your timeline.
- Analyze other timelines and models in the textbook that encourage a misconception. Design an accurate version of the scale or model.
- Design a geologic timeline or scale of the solar system based on the dimensions of a football field.
- Design a geologic timeline based on the 365 days of a year.
- Design a geologic timeline based on a 24-hour clock.
- Design an accurate scale drawing of the size of various dinosaurs relative to a human.
- Use an inflatable beach ball and a Styrofoam ball (or other appropriately sized ball) to represent the relative size of Earth and the Moon. Determine the correct amount of distance to place between Earth and the Moon to represent the correct span between them. (A 16-inch inflatable ball would be placed approximately 40 feet from a 4-inch Styrofoam ball or softball.)

The projects are to be completed outside class time and are due in a week.

**Evaluation**

A week later, for the final stage of Evaluation, each student has 5 minutes to present his or her research and findings to the questions and inquiries chosen during the Elaboration stage. Students are assessed on their ability to accurately present correct scientific information as well as their ability to communicate the information clearly to the class, including making proper eye contact and speaking clearly.
AN INTERVIEW WITH DR. TOM O'BRIEN

What does scientific inquiry mean to you?

Tom: Inquiry is the essence of science. Science starts with a base of prior knowledge, which in some cases may be partially correct or a misconception, and leads to an interaction with the world and having to test the data collected against reality. Inquiry, on the other hand, often involves encountering discrepancies that don’t make sense in light of what we know. Thus, we must engage in the Piagetian process of accommodation to reconstruct our prior understandings in light of new data when we synthesize both concepts. Inquiry is the evolution of our understanding. The metaphor of evolution is a very accurate one, because in evolution you have competing organisms and in different contexts. Sometimes a given theory becomes extinct because it is no longer suitably adapted to a changed environment that new data presents. Thus, our own personal mental theories and models about how the world operates constantly change to better fit a changing external reality.

What is the connection between inquiry and the 5E Learning Cycle?

We see inquiry throughout the entire 5E Learning Cycle. In the engagement phase, students are presented with a particular phenomenon that presents a challenge to what they know or believe to be true. In a sense, you are shaking up their present understandings and notions. Inquiry also involves generating questions at the start of a unit rather than saving them to the end. So much of our traditional high school teaching provides students with the answers to questions they never ask. In the Engagement stage, the discrepancy leaves questions that hopefully won’t be answered for a while. In contrast to verification lab work done in high school, the Exploration stage starts with a question, and you go about finding out how nature works. The conceptual piece lies in developing an answer after phrasing the question and doing the work to tease out of nature how it does work. The Explanation stage synthesizes and clarifies the range of results a class generates from the exploration. It’s natural for teachers to expect a range of students’ results because students’ technique of collecting data varies. Then there is still variation on what the data means and the students’ interpretation of the evidence. That’s an important idea to be highlighted during the Explanation stage. The Explanation stage also functions to relate the new phenomenon back to the students’ prior knowledge and make an assessment as to the validity of that prior knowledge. During the Explanation stage, you should have the opportunity to challenge some of what they know. Then, when we get to the Explanation stage, it is the teacher who provides a good interactive, multisensory lecture. There is a very good purpose for lecture when done at the right time. And that too is an inquiry process. So it becomes a dialogue more than a lecture. It becomes interactive teaching with a lot less “teacher talk.” So the Explanation stage is not just telling them the answers. Because if you did that, it would invalidate their work and students would get on to that real quick… Why put in the energy when the teacher is going to tell you the answers anyway?
Do you think some science textbooks unintentionally foster misconceptions on scale and structure? How does the “Toilet Paper Timeline” differ from other timelines in earth science textbooks?

There are some areas where you cannot show pictorially what the actual number represents. Take, for example, the concept of a mole. How could you possibly fit $10^{23}$ in a textbook? Or how about the relationship between the sizes of or distance between Earth and the Moon? I have not yet seen any textbook that accurately portrays the scale of relationship correctly. It is possible, however, to show the relative size and distance of Earth and Moon on a two-page spread. So all the pictures students see of the planets and the solar system are incorrect, yet as teachers we seldom take the time to tell students this. If you look at the timeline, it should read “Not to Scale” because equal distances on the timeline do not mean equal amounts in time. We need to supplement this diagram with activities that present a realistic relationship of scale and structure. That’s where the “Toilet Paper Timeline” is so good. It lets students discover the truth! Let’s say we wanted to introduce the notion of a million. The teacher can begin by placing a hundred marbles in a jar and then ask, “How many jars do we need to represent 10,000 marbles? 100,000 marbles? A million marbles? A billion marbles?”

Most textbooks underestimate the awesomeness of reality, and that essentially creates misconceptions. They actively teach something that is not true. Interestingly enough, the scale, as wrong as it is, can become a perfect evaluation instrument. For many teachers, the textbook becomes the bible, even though there are many things that are downright inaccurate. Sometimes graphical inaccuracies are a necessary evil, given the constraints of textbook dimensions. An eight-and-a-half by eleven-inch page does not do justice to a geological timeline. But that’s what the authors ought to challenge students to think about. Sometimes all we are given is a squiggly line to represent some span of time not represented on the page. An essay question that leaps out at me is “Compare the timeline in the book to your toilet paper timeline. How are they alike, and how are they different? And specifically, what are the problems associated with the textbook?” To analyze the difference between reality and what they see in their textbooks. Plus, look at the animals represented in each of the eras. Each animal is represented as the same size. A dinosaur looks the same size as a tree shrew. And all of that would be fine if you provided the natural limits of the drawings. In a very real sense, the textbook lied, but it didn’t tell you it lied. If a picture is worth a thousand words, a wrong or incorrect picture is worth a thousand misconceptions. How does it misrepresent reality? And why do you think the publishers did this? Is it possible to provide anything to scale in the confines of a textbook page? You might be able to do that if you devoted the entire textbook to just showing the historical timeline. I suspect the timeline would run the entire length of the pages. If evolution is an important theme in biology and earth science, can you run an accurate scale in the entire textbook? We need to help students toward critiquing the limitations of any science textbook to capture the true wonders of the physical universe.

Is a billion a difficult concept for high school students to understand?

Well, first of all, so much of what we try to do in science is to take a concept or idea that took thousands of years to develop and try to present it overnight. We think that we give students this one-shot presentation and they’re supposed to get it. My
argument on this would be that the notion of scale, which is important in all sciences, which helps explain how the world works, is well outside the range that people commonly conceptualize. And even though, at the high school level, we use exponents and power to the nth degree, many students don’t truly grasp that idea. And so what students need are multiple experiences with the concept, which ought to be dealt with in both math and science. There are, fortunately, many ways of doing that. I feel it’s unusual for any middle school students to get a sufficient understanding of scale at the middle school level to prepare them for high school science. You seldom find any articulation in the K–12 curriculum to prepare students for the kind of thinking they will do to handle the meaning of such large numbers. Some schools are struggling to develop curriculum maps just for this purpose, but for the most part, it is not formed by research. The bottom line is that scale is an absolutely pivotal concept in math in multiple sciences. And for the most part, we don’t teach the themes of scale very well.

**QUESTIONS FOR REFLECTION**

1. How can high school teachers use the theme of *evolution* to integrate biology and earth science?

2. Why is the age of Earth so important to the theory of evolution?

3. What religious and/or political issues surround the concept of a geological timeline and evolution? How would you deal with them?

4. Why do students have difficulty conceptualizing large numbers such as a billion?

5. What are the essential knowledge and skills students should have after studying the geologic timeline?

6. How can teachers use textbook inaccuracies to develop scientific habits of mind and understanding the nature of science?