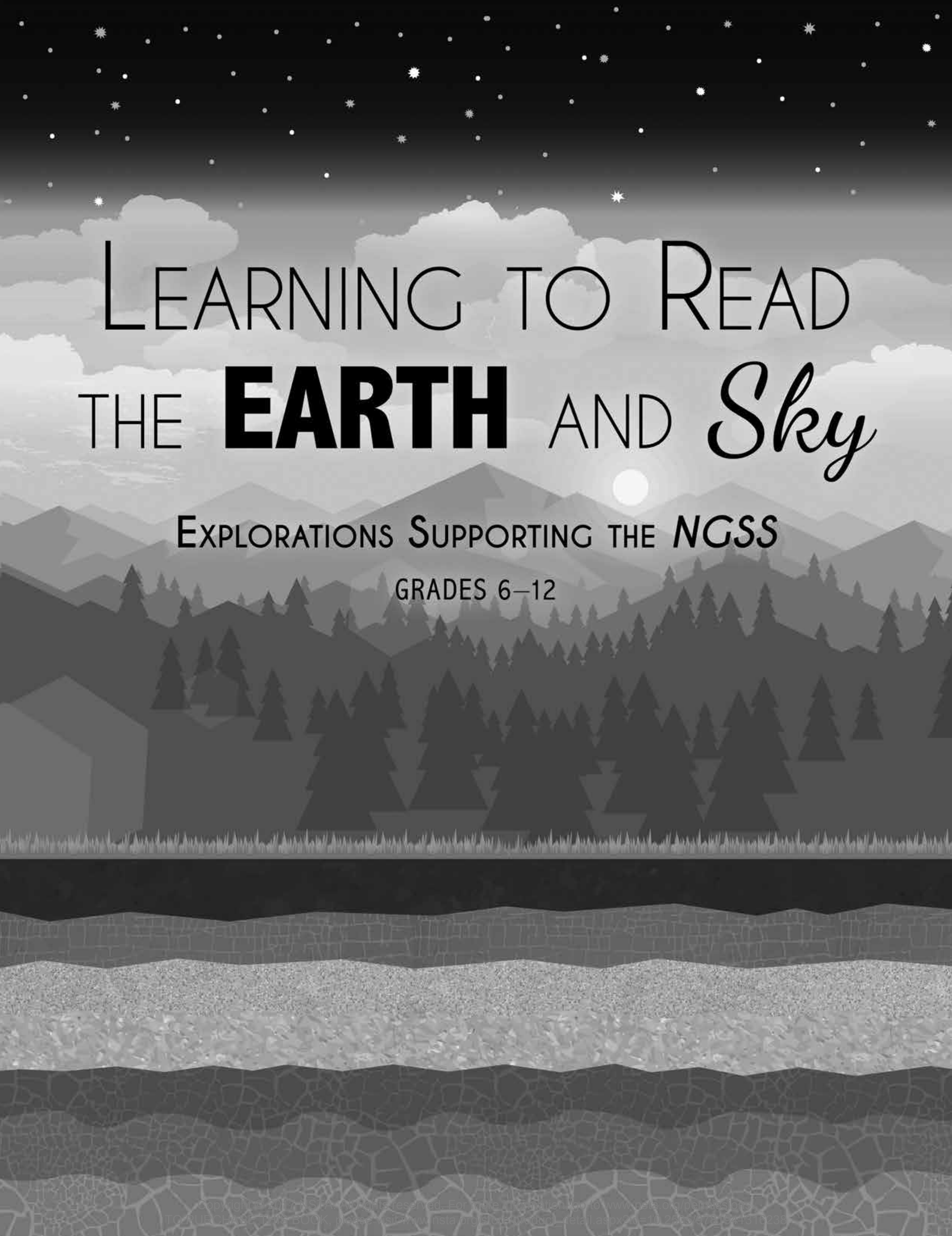
Learning to Read the EARTH and *Sky*

Explorations Supporting the *NGSS*

GRADES 6–12

Russ Colson
Mary Colson

NSTA press
National Science Teachers Association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CONTENTS

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ABOUT THE AUTHORS

Russ Colson and Mary Colson have spent much of their careers at the intersection between scientific research and science teaching. They have coauthored papers in peer-reviewed journals on topics ranging from the mysterious death of hadrosaurs in South Dakota to the nature of chromium dimers in silicate melts. They have applied those research insights to classroom investigation, publishing activities for teachers and giving multiple workshops on authentic science in the classroom. Many of the insights and activities in this book come from conversations and arguments on the nature of science, research, and teaching shared during field trips and lunchtime discussions. Through this experience, they have come to truly believe that science in the classroom and science in the research lab need not differ in their core approach.

Russ Colson has worked for more than 20 years as a professor of geology, planetary science, and meteorology at Minnesota State University Moorhead (MSUM). He has engaged hundreds of future teachers in field trips and laboratory science, including opportunities for many undergraduates to present research at national conferences. He founded two successful new programs at MSUM—Earth Science Teaching and Geosciences—and served as director for two education grant programs—Transforming Teacher Education at MSUM and Research Experiences for Teachers. He was a member of the team for the Minnesota earth science teacher licensure standards. In 2010, he was selected by the Carnegie Foundation and the Council for Advancement and Support of Education as one of four national winners of the U.S. Professors of the Year award.

Russ's research experience includes work as an experimental geochemist at the Johnson Space Center in Houston, Texas, and at Washington University in St. Louis, Missouri, where, among other things, he studied how a lunar colony might mine oxygen from the local rock. He put together an experimental petrology laboratory at MSUM with funding from the NASA and the donation of an electron microprobe from Corning. He twice received the university's top award for research involving undergraduates.

Russ has published 18 science fiction stories and articles and enjoys landscaping and gardening at his rural Minnesota home.

Mary Colson teaches eighth-grade earth science at Horizon Middle School in Moorhead, Minnesota, having taught previously in Texas and Tennessee. Her teaching is characterized

by investigation-based curriculum, which she creates herself and changes regularly. She has developed field-based projects, including grant-funded work at a local city park and a water quality research project on local wetland. She was named the middle school recipient of the 2008 Medtronic Foundation's Science Teaching Award presented by the Minnesota Science Teachers Association.

She served on the Minnesota Science Teachers Association Board of Directors for eight years, including a term as president, and then served as the elected District IX director for the National Science Teachers Association Council. She worked as a member of the *Next Generation Science Standards (NGSS)* writing team and was subsequently an educational consultant with Achieve Inc. to develop sample evidence statements and science/math tasks for the middle school and high school *NGSS* for Earth and Space Sciences performance expectations.

Mary holds a master's degree in geological sciences and earned her teaching licensure through the University of Tennessee Lyndhurst Fellowship Program, a competitive paid graduate program designed to recruit teachers from the ranks of trained scientists.

Mary is an avid outdoors person, explaining her wide-ranging field experiences, but also enjoys making a good quilt on a winter evening.

ABOUT THIS BOOK

Learning to Read the Earth and Sky is filled with informative visuals that enhance the book's content. We have provided an online Extras page to host full-color versions of many of the book's images. Feel free to print those images, as needed, for classroom instruction. You can access the Extras page at *www.nsta.org/learningtoread.* Throughout the book, images that are available on the Extras page are marked with the following icon: .

You will also notice that this book differs from other NSTA Press books in its use of *earth* and *Earth.* Whereas other NSTA Press publications use *earth* to refer only to soil and *Earth* in all other instances, we have chosen to strictly reserve *Earth* for references to the planet—including not capitalizing *earth science* as a discipline. This style convention is very important to us and at the heart of what we perceive as a long-standing misconception of what earth science is about. You can read more about our usage decision in "The Language of the Earth" section of the introduction (p. xx).

Bringing the universe into the classroom on a scale that students can investigate and discover

Inspiring teachers to reach beyond prepared curricula and explore science with their students

INTRODUCTION

In 1997, a group of college students, a pickax, and I (Russ) were scrambling along a rural gravel road in western North Dakota. The brisk wind cut through our thin jackets as the Sun fell behind a bank of clouds on the horizon. After six weeks of lectures in Geology in the National Parks, students at last had a chance to discover geology for themselves. They gathered around the young woman with the pickax, eyes drifting from the soft yellows and browns in the nearby buttes to the deepening hole in the grey rock. About a foot below the surface, the pickax began to dredge up crisp, black imprints of willow leaves. Eyes widened and interest quickened. "How could it be wet enough for willow trees to live here on the dry plains?" "How did they get into the rock?" "How long ago was it?" Suddenly, science became something to figure out, not just something to know.[C1]

And that's exactly what science should be, something to figure out, not just something to know. Telling stories to children does not teach them how to read a book, and telling facts, laws, or principles does not teach students to read the stories written in the earth and sky. *Learning to Read the Earth and Sky* explores the *doing* of earth science—how we read the stories written in the earth by applying the practices of science.

Appropriately, the *Next Generation Science Standards* (*NGSS;* NGSS Lead States 2013) emphasize science as a practice, not as a body of knowledge. Science is not about what we know, or think we know, so much as it is about how we know it. It is the person who *knows how we know* that participates in science. Only that person can reasonably discuss whether our understanding of the world is true or false. Anyone else must either accept or reject an idea based on their faith in the person who told them.

Along with science as practice, the *NGSS* emphasize the Earth as a complex, interacting system. In the natural world, everything is connected. John Muir recognized this interacting connectivity when he said "When we try to pick out anything by itself, we find it hitched to everything else in the Universe" (Muir 1911, p. 110).

So, the *NGSS* encourage both doing science in the classroom—the science and engineering practices—and learning the complex interplay of systems over the whole Earth and space beyond—the disciplinary core ideas (DCIs). The problem is that *you can't bring an all-encompassing supersystem into the classroom even if middle or high school students were able to understand it.* In fact, trying to capture the whole sweep of everything at once is contrary to the historical practice of scientific research—scientists break complex problems into bite-size, solvable chunks. In discussing the solution to a complex, interconnected problem in his book *A Brief History of Time,* Stephen Hawking (1996) notes that "it might be impossible to get close to a full solution by investigating parts of the problem in isolation. Nevertheless, it is certainly the way that we have made progress in the past" (p. 12). *Learning to Read the Earth and Sky* offers ways to break the immensity into small chunks that we can bring into the classroom.

Teachers might be concerned that the all-encompassing DCIs of the *NGSS* cut the link to more familiar big ideas of earth science. For example, the *NGSS* do not specifically identify classic ideas such as telling stories from rocks and strata (the wellspring of nearly everything we know about Earth's past), the movement of cyclones and fronts (the traditional foundation for understanding weather), or the processes that shape planetary surfaces (one of the primary new discoveries of the last half century). Instead, the *NGSS* DCIs emphasize interactions and cycles within Earth and space systems. Thus, for example, one of the components of the *NGSS* DCIs becomes this ESS2.A grade band endpoint for grade 8:

> *The planet's systems interact over scales that range from microscopic to global in size, and they operate over fractions of a second to billions of years. These interactions have shaped Earth's history and will determine its future. (NRC 2012, p. 181)*

Another component becomes this ESS2.C grade band endpoint for grade 8:

> *Water continually cycles among land, oceans, and atmosphere via transpiration, evaporation, condensation and crystallization, and precipitation, as well as downhill flows on land. (NRC 2012, p. 185)*

Does this mean that the traditional big ideas are no longer a part of the standards put forth for teaching earth science? No, of course not. They are all in there (along with, no doubt, the kitchen sink). The *NGSS* DCIs are less a limitation on what factual information all students should learn than they are a philosophical proposal that whatever students learn about earth and space processes, they should learn within the context of how that component fits into a bigger picture of a system of interacting subsystems.

FOUR PREMISES OF THIS BOOK

Our goal in writing this book is to provide concrete examples of classroom exploration that meet the ambitious goals of the *NGSS* to both teach science as a practice and reach toward an understanding of how all the small parts fit into a greater whole. We offer some of our own experience in bringing the entire universe into the classroom on a scale that students can test and discover, and we break down the sweeping DCIs into specific examples that students can see, touch, and experience.

We start with the four premises that are described in the following sections:

1. Earth science should engage students with the world they know.
2. Teacher and student are colleagues and fellow scholars.
3. Doing earth science requires breaking big concepts into smaller chunks.
4. The purpose of experimental and observational activities in the classroom is to practice doing science, and not to convey factual information in an active and "hands-on" way.

Engaging Students With the World They Know

Nicolas Desmarest was an influential figure in a heated 18th-century controversy over how rocks form. Did they form by cooling of volcanic lava or by crystallization and settling from seawater? Through careful fieldwork in which he mapped the connection between volcanic rocks and volcanoes, he showed an undeniable link between basaltic rocks and the volcanoes of central France, a contribution that swung the verdict to the belief that some rocks form from volcanic lava. When asked in his old age about the "truth" of the matter, rather than reassert his own views, he responded simply "Go and see!"

Thus, Desmarest reminds us that science doesn't begin with theoretical ideas or facts but rather with the belief that we can understand our universe through observation. Like science research, effective science teaching begins with what students can see, feel, and explore, not with theoretical ideas. Earth science in particular deals with phenomena that people can see and experience all around them—rocks, rivers, clouds, and wind. To improve teaching in the classroom, the DCIs of the *NGSS* must be reduced to a scale that students can "go and see."

Seeing alone is not enough. To do science, students and teachers must understand what they see and what it tells us about how the world works. Earth science is not about knowing the laws of nature, or even knowing the stories of Earth's past. Earth science is about *reading* the stories written in the earth and sky, the *practice* of science.

Addressing aspects of our universe that students see and experience, and teaching students to read those stories on their own, gives them ownership in the process of discovery. They realize that science is not something they are told, coming from high oracles of the mysterious science world. Science becomes something that people *do,* something that *they* can do.

This book is not just a "rule book" of science. It is a book of practice, showing how to dribble, how to pass, and how to shoot in the game of earth science. It provides ways for teachers and students to practice the game together, remembering that science is what we do, not just what we know.[C1]

Teacher and Student as Colleagues and Fellow Scholars

In a brand-new science room in 2003, I (Mary) engaged my eighth graders with an old geology activity—crystallizing thymol in a petri dish. Like magma, thymol produces large crystals when cooled slowly and small crystals when cooled fast, illustrating the foundation for one of the key stories told by igneous rocks. But this time, something wasn't working for one of my groups. No crystals formed in their slow-cooled sample, and when crystals finally did grow, they were small. One student in the group looked at me with disappointment. "What did we do wrong?" he asked.

"I don't know," I said. "We'll have to figure it out."

The teacher doesn't know? She has to figure it out?

Postures shifted. Eyes brightened. We started asking questions. "It's cold, so why isn't it solid?" "What did the other groups do different?" "What can we try new?" The students hunched over the lab bench with renewed interest. Suddenly, the lab no longer dealt with getting the "right" answer from the teacher's key. Now the lab dealt with how they could figure out something that the teacher didn't know. In the accident of the lab "not working," it had become real science.

Some comparisons and experimentation led them to the conclusion that, if they melted the thymol entirely, crystallization was delayed because of an absence of "seed" crystals. When it finally did crystallize from a supercooled state, it did so rapidly, producing small crystals. But the real discovery of the activity was that science is about figuring things out, not waiting for the teacher to hand out the answers.

We believe that the authentic teacher engages in discovery with her students, asking her own questions, developing her own exploratory activities, analyzing and interpreting results that don't always seem to make sense. Sometimes labs developed in this way may not be completely polished, and the results not completely certain, but the challenges that arise are not a problem to be avoided. The challenges and uncertainties are the whole point of the activity. In taking up those challenges, the teacher gives students the valuable learning experience of seeing her doing science, not just assigning activities and following recipes that someone else developed. Not only do the students realize that the teacher values true exploration, but they see and learn from the way the teacher asks questions and tests ideas.

Early in my (Russ's) career at Minnesota State University Moorhead, an older faculty member in the education department characterized a teacher as a pipeline through which knowledge flows to the student. This image didn't work for me. Doing science is no more about passive knowledge than playing basketball is about knowing the rule book. The teacher is better characterized as coach, illustrating good science reasoning skills—by sometimes allowing himself to get stumped and having to figure out a puzzle in front of the students—and then giving students the chance to practice solving their own puzzles.

Teachers often look for polished and well-tested activities to do with their students. This is fine to do on occasion—the teacher only has so much time, and the next class period is already pressing. But the point of teaching is not to make it easy on the teacher or the student. *Easy* is giving students a recipe lab where they follow the simple instructions to the inevitable outcome. *Good* is crafting situations where students struggle to figure out what to do, grapple with concepts, and have to ask lots of questions. Some labs should be of this latter type. And some should be of the teacher's own making.

This book provides some activities that we have tested and find useful for cultivating student reasoning and discourse in the classroom. More important, it provides insight into the process of doing science that can help us all be more authentic teachers, developing our own activities and providing the foundation so we can truly say, "My students and I do science together."

Breaking Big Concepts Into Smaller Chunks

Back in the 1980s, a humorous list of test questions circulated among PhD candidates preparing for their preliminary exams. Each of the questions captured the expectation that candidates should provide comprehensive, detailed answers for vaguely worded, abstract, and far-reaching questions. One of the questions was something like "Explain the universe. Give three examples."

The *NGSS* propose that a key outcome of education should be that every student understands Earth's complex systems and how they interact— that students understand Earth's place in time and space and how human actions impact broad planetary processes in complex ways. Although this is an important goal, it may be seen as vague, abstract, and far-reaching. In our view, it's difficult to get to these big-scale understandings without first engaging in much smaller-scale science exploration. The good news is that the "big-picture" goals of the *NGSS* do not limit the small-scale science that the teacher can bring into the classroom. All of earth science, its core discoveries, its methods of investigation, and its stories of past and present, fit comfortably within the broad learning outcomes of the *NGSS*. That's not to say that all of earth science should be brought into the classroom. Trying to cover "all the material" causes a class to devolve into a listing of facts and concepts without time for the actual practice of science exploration. However, the big-picture *NGSS* goals can be reached through a doable subset of classroom-size science explorations.

In real research, scientists might be studying the chemical evolution of the Moon, but their work will focus on a small subcomponent of how that evolution works. Likewise, students might examine how "water continually cycles among land, ocean, and atmosphere," but in the classroom they will look at how water condenses out of air. The job of the teacher is to make choices that limit the scope of the topic, allowing time for students to truly explore some subset of a larger system, while tying what the students are doing into an understanding of that system. The small-scale classroom work helps students understand *how things work and how we know,* while the bigger picture gives them a conceptual understanding of the elegant workings of our world and universe.

New teachers fresh out of college often feel like they have lots of material to cover. For example, they might have ideas about atmospheric circulation and climate, seasons, movement of energy, ocean currents, and how they all work together. But how do you pare that down to something that middle and high school students can do in the classroom? Maintaining a sense of the big picture without getting lost in the sea of details, while still giving students a real experience in science exploration, depends, like real research, on breaking the big picture down into small, solvable components.

Although teachers need to limit what they bring into the classroom, we should not limit the scope of the discipline by predefining a subset of material that every class must encompass. Rather, we should limit the number of examples we use to illustrate the bigger ideas while maintaining the full scope of the discipline as fair game for learning. This book offers examples of specific, small-scale activities that you can do in the classroom, along with connections to the big-picture ideas of the *NGSS* to which the activity applies.

Using Experimental and Observational Activities in the Classroom to Practice Doing Science

Fads are common in teaching. Some of these fads are of lasting importance, while others fade away, yet each one is portrayed as revolutionary and the "final word" at the time. Some fads introduce important new ideas that may not be fully understood until later. A couple of decades ago, "inquiry-based science" was the big thing, raised to importance by *Benchmarks for Science Literacy* (AAAS 1993) and the *National Science Education Standards* (NRC 1996). Its intention was not unlike the science and engineering practices proposed by the *NGSS,* and thus of lasting importance, but in application the pursuit of inquiry often became confused with the use of activities to convey factual information. For example, instead of a teacher telling students about the thicknesses and character of Earth's core, mantle, and crust, the students might color, cut out, and assemble a premade model of Earth's interior—a pedagogically sound activity for learning a concept but not one that engages students in the scientific process.

Thus, inquiry-based science, intended to prompt teachers to do science with their students, sometimes became an alternative avenue for conveying science knowledge. Why? Because doing real science is a lot harder than conveying information. It's hard to create activities. It's hard to interpret the results. It's hard to interact one-on-one instead of as a whole class. And it's especially hard to re-create in the classroom the sense of science discovery that in real life took thousands of scientists hundreds of years.

Teachers don't have hundreds of years in the classroom, and yet they want to give students a sense of the exploration and discovery inherent in science. The secret is to limit the options that students need to consider. Without sufficient limitations, the classroom lab devolves into random experiments that provide little or no insight into the science. With limitations set too tight, students have no real creative or analytical input and the lab becomes a "lecture by activity" in which the goal is to reinforce the content knowledge or derive the "correct answer."

It is helpful to have specific examples of how to apply limits to classroom investigations. Those limits depend on the ability level of the students and on the materials and time available. It is also helpful to have examples of obstacles that students are likely to encounter and misunderstandings they are likely to entertain. This book offers example activities and stories from the classroom that can help guide the teacher in setting those limitations while still providing a meaningful experience in science discovery.

ORGANIZATION OF THIS BOOK

The main part of this book is organized into three sections: "The Practices of Science," "The Language of the Earth," and "YOU Can Do It!" These sections are described in the pages that follow. After these sections are the afterword and three appendixes. The afterword includes a brief discussion of some aspects of teaching that we did not cover in depth in the main sections. Appendix A lists chapter activities and anecdotes related to *NGSS* performance expectations. Appendix B lists chapter activities and anecdotes related to *NGSS* science and engineering practices, DCIs, crosscutting concepts, and performance expectations. Appendix C provides illustrative quotes for selected ideas presented in the introduction and individual chapters. The quotes highlight a few of the significant ideas in science education that have been explored by teachers and researchers. Throughout the book, discussions corresponding to selected ideas in Appendix C are noted by a superscript *C*, followed by the note number.

The Practices of Science

Science is something we do, not something we know. The *NGSS* emphasize teaching science as a practice. *Learning to Read the Earth and Sky* devotes nine chapters to examining the practices of science, offering sample earth science activities for the classroom and anecdotes that illustrate student challenges and misunderstandings. Our goal is to help students and teachers understand the basic tools and language of science: how to propose and investigate a question that can be answered through science, how to analyze and interpret data, how to create and use a scientific model, and how to explain and communicate a scientific theory. We explore how an experiment differs from a learning activity, how to use graphs and maps, what scientific modeling means, and how to reason from evidence to theory.

The Language of the Earth

More than any other science, earth science is about stories: stories of Earth's past, stories of how things work, stories of how we know. Most of the great discoveries of geology are hinged on learning how to read those stories. The key "content" is not the conclusions of scientific studies—models, theories, and natural "laws." Rather, the key content is an understanding of how we read the stories. Many of these story-reading skills are unique to earth science—the place where it is set apart from chemistry, physics, and biology.

Learning to Read the Earth and Sky devotes five chapters to methods we use to read the stories written in the earth. Although the *NGSS* embeds these story-reading skills (the grammar of the earth, if you will) within the DCIs, we think there is a need, when applying these story-reading ideas in the classroom, to break them out. Without an understanding of these earth-reading concepts, any effort to examine Earth systems becomes an exercise in accepting the "facts" that someone gives without any real understanding of the underlying science. We consider in particular (1) how we read the story of Earth's past as written in earth—the soil, sediments, and layers of rock that make up our planet; (2) how we figure out the nature of places we can never visit, such as distant stars and the Earth's core; and (3) how we track down the movement of elements through the complex cycles and systems of the Earth.

Earth science emerged as people learned to read the stories of Earth's past and present written in its lithosphere, hydrosphere, atmosphere, and biosphere. Today, we apply these same language skills to reading the stories of other worlds written in their own "earthy" materials. In this book, we leave the first "e" in earth science lowercase to remind ourselves that the skills and practices of earth science now apply to more than planet Earth alone.

YOU Can Do It!

We believe that teachers should do science with their students. *Learning to Read the Earth and Sky* devotes three chapters to examining the teacher's role in this collaboration: teacher as curriculum narrator; teacher as guide in starting where you and your students are; and teacher as mentor, practitioner, and scholar.

The teacher, as *curriculum narrator,* can tie spontaneous and small-scale classroom exploration to the big ideas of science. The DCIs of the *NGSS*—and John Muir—tie everything in the universe to everything else, focusing our attention on the elegant way that the universe works in great systems and cycles.

Teachers can engage students *where they are.* We propose that students are most engaged with discovery when they investigate events and places that they know.

Teachers can be *mentors* and *practitioners of science.* We argue that students should be neither rigidly directed by the curriculum nor allowed to flounder with too little guidance. Instead, students should be provided a middle road where they make real choices in what investigations to pursue and how to pursue them, under the guidance of an expert mentor and practitioner of science—the teacher.

Scientists are sailors on the ship, not passengers, and understanding science is about understanding how to sail the ship. If we as teachers don't do a bit of the sailing with our students, then neither we nor they can ever really understand what science is all about.

Safety Practices in the Science Laboratory and Field

Both inquiry-based classroom and laboratory/field activities that immerse students in the practices of science can be effective and exciting. To ensure the success of these activities, teachers must address potential safety issues relative to engineering controls (ventilation, eye wash, fire extinguishers, showers, etc.), administrative procedures and safety operating procedures, and use of appropriate personal protective equipment (indirectly vented chemical-splash goggles meeting ANSI/ISEA Z87.1 standard, chemical-resistant aprons and nonlatex gloves, etc.). When personal protective equipment is indicated for use in an activity's safety notes, it is required for all phases of the activity, including setup, hands-on investigation, and takedown. Teachers can make it safer for students and themselves by adopting, implementing, and enforcing legal safety standards and better professional safety practices in the science classroom and laboratory/field. Throughout this book, safety notes are provided for activities and need to be adopted and enforced in efforts to provide for a safer learning/teaching experience.

Teachers should also review and follow local policies and protocols used within their school district and/or school, such as a chemical hygiene plan and Board of Education safety policies. Additional applicable standard operating procedures can be found in the National Science Teachers Association's (NSTA) *Safety in the Science Classroom, Laboratory, or Field Sites (www.nsta.org/docs/SafetyInTheScienceClassroomLabAndField.pdf).* Students should be required to review this document or one similar to it under the direction of the teacher. Each student and parent/guardian should then sign the document to acknowledge that they understand the procedures that must be followed for a safer working/learning experience in the laboratory. An additional reference is available for teachers to further explore field trip safety considerations: *Field Trip Safety* by the NSTA Safety Advisory Board *(www.nsta.org/docs/FieldTripSafety.pdf).*

Disclaimer: The safety precautions for each activity are based in part on use of the recommended materials and instructions, legal safety standards, and better professional practices. Selection of alternative materials or procedures for these activities may jeopardize the level of safety and therefore is at the user's own risk.

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ANALYZING AND INTERPRETING DATA, PART 1

GRAPHING

To understand a graph, it's important to remember that graphs represent real-world observations. Graphing is a language that turns an initially puzzling blizzard of real-world data into a coherent story.

Back before stories went viral on Twitter, anonymous jokes circulated by e-mail. I (Russ) received one such e-mail on March 20, 1999, that illustrated the complexity of crunching through a large body of observations to reach a synthesizing conclusion.

> *Sherlock Holmes and Dr. Watson went on a camping trip. After a good meal and a bottle of wine they lay down for the night, and went to sleep. Some hours later, Holmes awoke and nudged his faithful friend.*
>
> *"Watson, look up at the sky and tell me what you see."*
>
> *Watson replied, "I see millions and millions of stars."*
>
> *"What does that tell you?" says Holmes.*
>
> *Watson pondered for a minute. "Astronomically, it tells me that there are millions of galaxies and potentially billions of planets. Astrologically, I observe that Saturn is in Leo. Horologically, I deduce that the time is approximately a quarter past three. Theologically, I can see that God is all powerful and that we are small and insignificant. Meteorologically, I suspect that we will have a beautiful day tomorrow. What does it tell you, Holmes?"*
>
> *Holmes was silent for a minute, then spoke.*
>
> *"Watson, you idiot. Someone has stolen our tent."*

With the last sentence, obscure elements, such as why Holmes woke him up and how a unique solution to the question is possible, become clear. There is a point in an investigation when new observations are no longer bewildering but fit neatly into a growing understanding. At that point, we gain the ability to predict future observations.

ORGANIZING THE BEWILDERING

Graphs bring large numbers of bewildering observations together in a single, coherent picture. They provide a means to explain how variables are related to each other and can be a starting point for evaluating possible cause-and-effect relationships. They provide a way to make predictions based on correlations between variables, which can be used to test whether the correlations are causative or not. To develop those explanations and make those predictions, we need to understand the language of the graph.

In this chapter, we offer a quick journey through reading a graph. As you review the case study and the subsequent sections on working with graphs, pay attention to the habits of mind that you use and think about how you might guide students in developing those habits.[C10]

Considerations in Learning the Language of the Graph

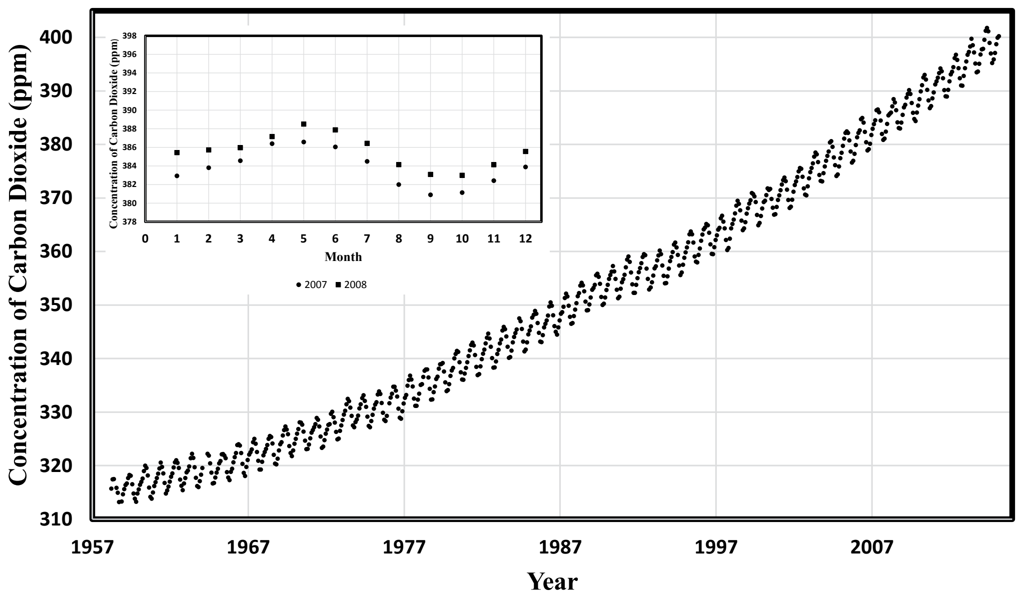
- Does this graph plot variation in one parameter against another? Most graphs used in experimental science do, but bar graphs don't.
- What are the labels on the axes? How do the values apply to the real world? Do you need students to explore any aspect of the labels? For example, on the Keeling Curve discussed in this chapter, would your students understand the idea of *concentration in ppm?*
- Is there a correlation or not?
- If there is a correlation, is the relationship linear or not linear? What does that mean in terms of real-world behavior?
- Is the slope positive or negative? What does that mean in the real world?
- What is the value of the slope? What does that mean in the real world?
- If there is a correlation, is there a causal relationship? What is your evidence? What predictions can we make from that causal relationship?
- If there appears to be a correlation, is it real—that is, is it greater than the uncertainty in the measurements? Is the scatter in the data around a correlation trend smaller than the change in value due to the correlation?

A CASE STUDY IN GRAPH READING

Let's consider a classic graph from the earth sciences that continues to have a significant impact on national policy. The Keeling Curve shown in Figure 4.1 is a record of the concentration of carbon dioxide (CO_2) measured at the top of Mauna Loa since 1958.

Figure 4.1

The Keeling Curve charting the measured change in carbon dioxide in the atmosphere at the summit of Mauna Loa in Hawaii



Note: ppm = parts per million.

Sources: Based on data from *ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt.* Carbon dioxide data were collected by David Keeling of the Scripps Institution of Oceanography (SIO) before 1974 and by both the SIO and the Earth System Research Laboratory at the National Oceanic and Atmospheric Administration since then.

What does this graph tell us? We see that the amount of CO_2, in parts per million (ppm), is plotted on the y-axis and time is plotted on the x-axis. The concentration of CO_2 since 1958 is not constant but increases to the right, telling us that the concentration of CO_2 is increasing with time.

We can see that the trend is not linear, but rather the slope of the trend becomes steeper with time—notice that you can't draw a single straight line through data for all years. This means that the rate of increase in CO_2 has itself been increasing, which is consistent with humans burning more fossil fuels and making more cement in the 2000s than in the 1960s (although this correlation does not prove that human activity is the only cause of this increase). We can see that the trend in the data does not intersect the y-axis at zero on the left-hand side of the graph, meaning that some CO_2 was already present in the atmosphere in 1958.

We also notice a peculiar sawtooth pattern to the variation in CO_2 concentration. From the inset on the graph, we see that each rise and fall is exactly one year long. Each year, the concentration increases from about October (month 10) to May (month 5) and decreases from about May to October. Like Sherlock's missing tent, this observation makes sense when we realize that from May to October, plants in the Northern Hemisphere are consuming CO_2 during their growing season. The zigzag pattern of the Keeling Curve proves a strong *correlation* between variations in CO_2 and time of year. When combined with other evidence for seasonal variations in CO_2 due to plant respiration, this correlation provides a strong case that the zigzag variations are *caused by* seasonal variations in plant growth.

Discovery of the Carbon Dioxide Annual Cycle

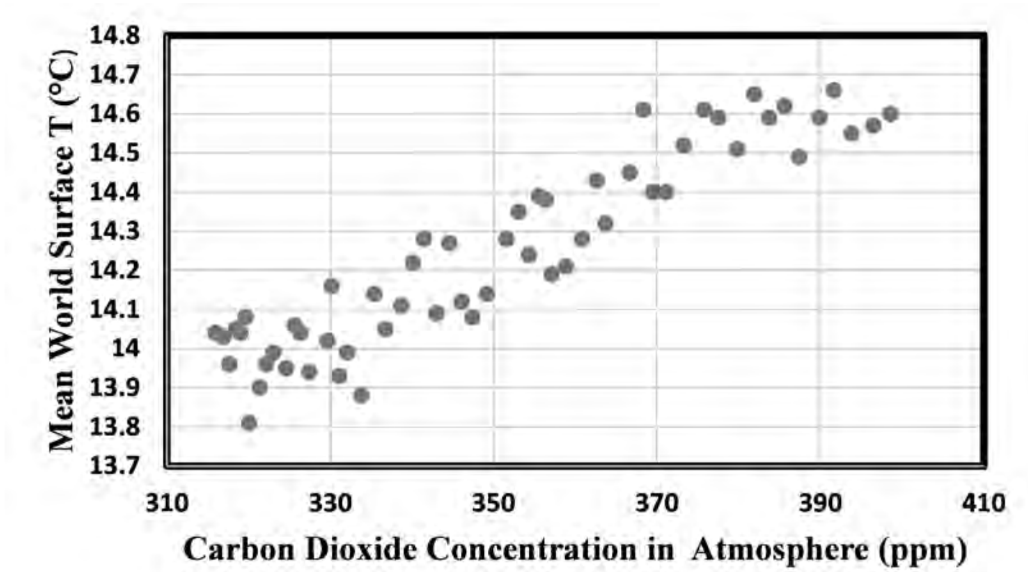
In the mid-1950s, Charles David Keeling developed a system for measuring the carbon dioxide (CO_2) concentration in air. As a postdoctoral fellow at the California Institute of Technology, he measured the CO_2 concentration in forests and grasslands, places where the air would be more affected by natural biological activity than by human activity. He discovered that air impacted by the forests and grasslands showed a regular daily cycle in CO_2. He was able to relate the cycle to respiring plants giving off CO_2 at night.

In March 1958, Keeling and his team began making CO_2 measurements on Mauna Loa. Unexpectedly, he found that the concentration of CO_2 at Mauna Loa rose from March until May and then declined until October. The same pattern repeated in 1959. In Keeling's own words: "We were witnessing for the first time nature's withdrawing CO_2 from the air for plant growth during summer and returning it each succeeding winter" (Scripps Institution of Oceanography 2016a, 2016b).

The Keeling Curve is often combined with measurements of world air temperature to show a correlation between CO_2 concentration and average global temperature (see Figure 4.2). In this graph, we see a strong positive correlation between CO_2 and temperature. A positive correlation means that they are both increasing together. We might jump to the conclusion that the increase in CO_2 is *causing* the increase in temperature. However, since these data come from field measurements and not from a controlled experiment in which only one variable is changed and another variable responds, the correlation does not necessarily imply causation.

The distinction between *correlation* and *causation* is an important one for students to consider. I (Russ) often present the difference this way: "Every morning I get up, and also

Figure 4.2
Correlation between the average annual concentration of carbon dioxide measured at the summit of Mauna Loa and average annual world surface air temperatures (T)



Sources: Based on data from *http://data.giss.nasa.gov/gistemp/graphs_v3/Fig.A2.txt* (for temperature) and *ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_annmean_mlo.txt* (for carbon dioxide). Carbon dioxide data were collected by David Keeling of the Scripps Institution of Oceanography (SIO) before 1974 and by both the SIO and the Earth System Research Laboratory at the National Oceanic and Atmospheric Administration since then.

every morning the Sun rises. Every morning! A clear correlation. Wow. I must cause the Sun to rise!"

Correlation simply means that two things happen together. However, a correlation does present the possibility that one change causes the other. The possibility that I cause the sunrise can be tested by making a prediction and seeing if the prediction is born out: If my getting up in the morning causes the sunrise, then we predict that if I get up at different times of the day the sunrise should follow (I have tried this, and, disappointingly, it doesn't work).

For the correlation shown in Figure 4.2, the case for causation is strengthened by other experiments showing that CO_2 absorbs infrared radiation—radiation that might otherwise escape into space—and so *could cause* the temperature of Earth to rise. Testing for causation by making a prediction such as we did with me and the sunrise would require that we produce different amounts of CO_2 over long periods of time and see how it affects world temperature. This is an experiment which, for better or worse, we are in the process of carrying out.

From Figure 4.2, we can also get a feel for uncertainty in the data and how that uncertainty affects our confidence in the correlation between temperature and CO_2. *Uncertainty* is one of the most important ideas of science. It's important for students to understand that correlations are never perfect, both because no measurement is ever exact and because real variation that is not explained by our correlation model might exist in natural data. Uncertainty is an estimate of how imperfect our measurements or correlation models might be.

As simplified in the following text, a graphical analysis of uncertainty can be done by students even without doing a lot of math. Although graphical statistics don't have the rigor of mathematical analysis, students get a feel for what uncertainty means and how it can be inferred from data.

Notice that values for temperature in Figure 4.2 vary from 13.8°C to 14.7°C and CO_2 concentrations vary from about 315 ppm to nearly 400 ppm. Although the variations in temperature and CO_2 are correlated, they are not perfectly correlated—that is, we can't draw a single smooth line or curve that passes through all the data points. We can think of the total variation as being the sum of the variation that goes along with the correlation trend (the variation explained by a curve through the data), plus any "extra" scatter around that trend (the amount of variation from the curve). This "extra" variation can be caused by many factors such as imprecisions in our measurements or real variation in the data that are correlated with other, unidentified causes. This extra variation gives us a feel for the uncertainty in the data.

You might have students consider the magnitude of the variation that is "explained" by the correlation and compare it with the magnitude of the remaining scatter around the trend. The smaller the magnitude of the scatter compared with the variation explained by the correlation, the more confidence we have that the correlation is real and not a random artifact of data variations. For example, in Figure 4.2 the total variation is a bit less than a degree, whereas the scatter is about 0.2 degrees. You might also have students draw a "maximum reasonable slope" line and a "minimum reasonable slope" line through the data. From these two trends, students can get a feel for how much the uncertainty might affect the slope of the trend.

NOT JUST A TECHNIQUE

Although students need to develop a number of technical skills to make graphs, such as proper scaling and proper plotting, the mechanics of drawing a graph are not the main point of data analysis, interpretation, and graphing as proposed by the *Next Generation Science Standards (NGSS).* For example, science and engineering practice 4 matrix for grades 6–8 in Appendix F of the *NGSS* includes this element: "Construct, analyze, and/or interpret graphical displays of data and/or large data sets to identify linear and nonlinear relationships" (NGSS Lead States 2013).

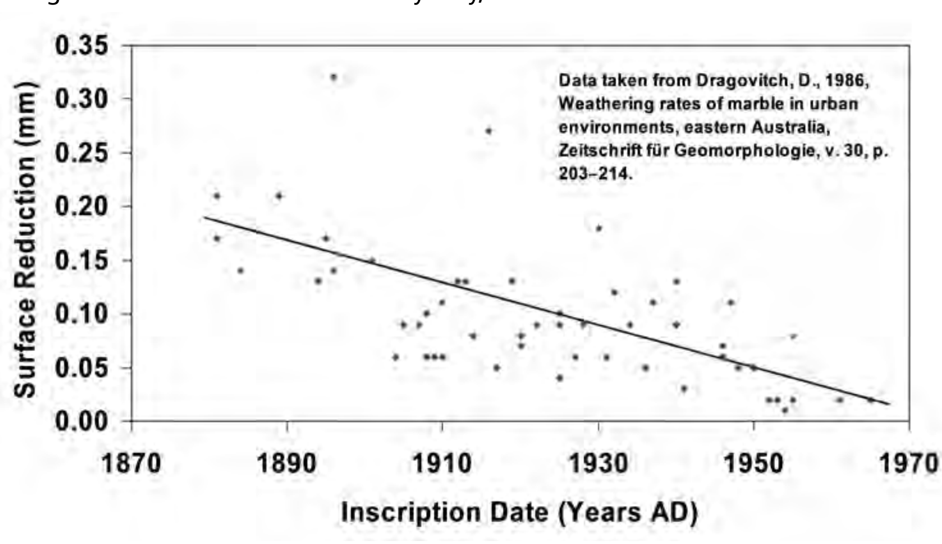
Nor do the technical mechanics of drawing a graph address the *NGSS* crosscutting concept of Cause and Effect: Mechanism and Explanation, as described in *NGSS* Appendix G for grades 9–12: "students understand that empirical evidence is required to differentiate between cause and correlation and to make claims about specific causes and effects."

In our experience, students are much better at plotting graphs than at understanding what the graphs mean. This struggle that students experience in connecting graphical data to lab and field observation has been reported by teachers and education researchers for many years, as pointed out, for example, by Robert Beichner in his 1994 paper "Testing Student Interpretation of Kinematics Graphs." Yet, deriving meaning from the graph is the main point of the graph. What does the slope represent? What does the y-intercept mean? How does the information on the graph relate to the natural system under study?

In 2014, I (Mary) had my students study graphs showing the rate of weathering of tombstones in Sydney, Australia (see Figure 4.3). I began with simple exercises such as considering whether the slope was positive or negative and what that might mean in terms of the rock changing through time. Then, I had students calculate the slope (millimeters per year). For technical reasons, some students ran into difficulties in calculating slope. In math, students sometimes determine slope by counting squares in a grid; some

Figure 4.3

Weathering rate of marble tombstones in Sydney, Australia



Source: Graph and activity developed by Rebecca Teed and published as "How Fast Do Materials Weather" in *Starting Point: Teaching Entry Level Geoscience*, available at *http://serc.carleton.edu/introgeo/interactive/examples/weatrate.html.*

students couldn't find slope because there was no grid on the graph. Other students tried to measure the rise and run with a ruler—not realizing that the scales of the two axes were quite different and plotted different types of values (millimeters vs. years). In science, graphs rarely plot dimensionless numbers against each other. To transfer math graphing skills to the science classroom, students need guidance in thinking about labels and scales on the axes.

Our conclusion is that students need to practice reading scientific graphs even if they know the mechanics for creating them. Students need practice thinking of numbers not as dimensionless values but as values connected to real-world measurements such as mass, temperature, and solubility. Students need practice relating trends on graphs to real-world processes and relationships.

We view reading a graph as a language skill, like learning to read a book, rather than a technical skill, like learning to write the letters of the alphabet. In the following section, we offer some ways to practice that language skill.

GRAPH-READING CHALLENGES

In learning to read and write in the language of the graph, students might practice translating graphs into real-world understanding or translating real-world data into graphs.[C11]

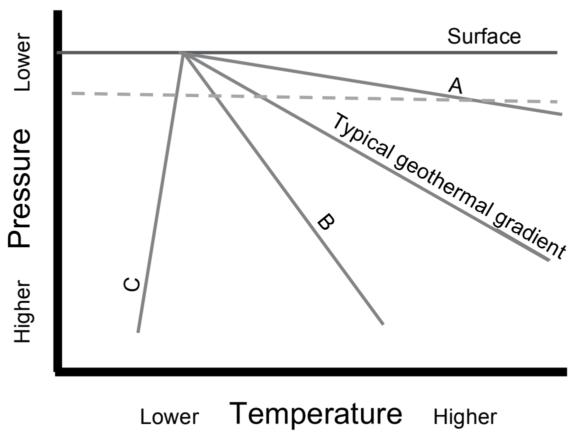
For example, in the activity with the tombstones, after students calculated the slope and associated that slope with a rate of weathering (about 2 mm/100 years), one student commented that it didn't seem like a very fast weathering rate. I (Mary) asked if the tombstone would still be there in a million years. That question launched the class into a calculation of how long it would take to weather the tombstone away completely, an activity that engaged them in translating the graphical information into a real-world application.

One way to practice going the other direction—translating observational data into a graph—is through the use of short graphing puzzles. I (Russ) often engage students in conceptual analysis of what observational data imply about the slope on a graph, or whether the observational data are most consistent with a positive or negative slope—basic concepts of graph reading that students often struggle with most. These puzzles are easy for teachers to create and adapt to a variety of lessons and topics.

For example, most students understand that the Earth gets hotter as one goes deeper. This increase in temperature with depth is called *geothermal gradient.* However, not all locations have the same geothermal gradient. Yellowstone National Park has magma near the surface, resulting in a higher geothermal gradient in that area. With a graphing puzzle such as that presented in Figure 4.4, you might prompt your students by asking which trend represents the geothermal gradient at Yellowstone (the one that's hottest close to the surface). For follow-up, you might ask, "What would be the temperature at the point the different trends converge?" and "What would be the physical meaning of the other trends?"

Figure 4.4

Conceptual graphing puzzle on the geothermal gradient at Yellowstone National Park



Prompt questions you might use with students include the following: Which line most closely portrays the high geothermal gradient present at Yellowstone National Park? What value for temperature or pressure do you expect where the lines converge? What is the real-world meaning of the other trends? Note that pressure is plotted on the *y*-axis—as you go deeper into the Earth, there is more rock above you and therefore greater pressure. The dashed line shows one particular depth, which can guide students in determining which trend shows the highest temperature at that depth.

When Experience Contradicts Learning

Many students have visited caves, usually on summer vacations with their families, and noticed that the air temperature *decreases* as they descend into the earth. It's cold in the cave, especially in contrast to the hot summer weather. And especially if one ignores the signs that say "Cave is cold, bring a coat!"

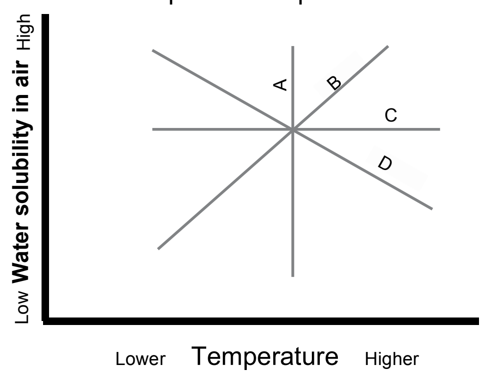
Students often ask how the Earth can get hotter with depth if caves are colder. Yeah. What's going on here? Which is it? Hotter or colder as you go down into the Earth?

Cave temperatures are often close to the average annual temperature outside the cave. They will indeed be cooler than the outside air in summer. But they are warmer in winter.

In Chapter 2, "The Controlled Experiment," we reported experiments for measuring the solubility of water vapor in air as a function of temperature. Suppose that you're working on a similar unit. You might prompt your students with the following puzzle (see Figure 4.5, p. 62): "Consider the observation that on a hot, muggy day, water condenses on a cold can of pop when you take it from the cooler out at the lake. If the water forms on the can of pop when the water condenses from the air, which trend line would represent how solubility of water vapor changes with temperature?" You might then ask these follow-up questions: "What would be the physical meaning of the other lines?" "Does a vertical line even make sense?" "Why or why not?"

Figure 4.5

Conceptual graphing puzzle on the temperature dependence of water vapor solubility in air



Prompt questions you might use with students include the following: Which of the lines best portrays the trend of solubility with temperature, given that water condenses on a cold can of pop on a hot, muggy day? What is the real-world meaning of the other trends (none of which actually occur in our dimensional reality)?

The vertical line (line A in Figure 4.5) doesn't make sense because it implies that only one temperature is possible and, at that temperature, water solubility in air simultaneously takes on all possible values. The horizontal line (line C in Figure 4.5) means that the water solubility does not change with temperature. Line D in Figure 4.5 implies that water vapor becomes more soluble with decreasing temperature, the opposite of the relationship observed.

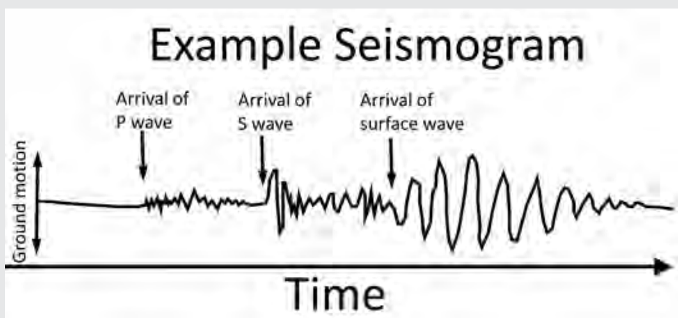
PAYING ATTENTION TO AXIS LABELS

You can't know what a graph is telling you if you don't know what's been plotted on it. Students often automatically and wrongly assume that the axis labels will correspond to whatever data they are given in a classroom problem.

For example, finding the location of an earthquake epicenter is a common classroom activity in which data from the seismogram and the graph axis labels don't match up. The input data are typically arrival times—the times when the P and S waves arrived at a seismograph—but the graph plots travel times—time elapsed between earthquake and arrival of the seismic wave at the seismograph.

Seismic Travel Time Analogy

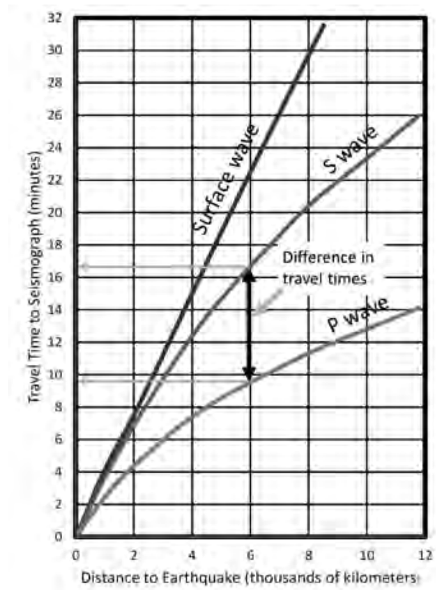
Measuring seismic arrival times is like noting that you saw a flash of lightning at 2:00 p.m. (the P wave) and then heard the sound of thunder at 2:00:25 p.m. (the S wave). To figure the distance to the lightning bolt, you use the difference in the arrival times of the light and the sound. Given that sound travels at about one-fifth mile per second through our atmosphere (1 mile every five seconds), the hypothetical lightning bolt was 5 miles away. From this, you can calculate the time of the lightning strike (because the speed of light is so fast, this is essentially the same as the arrival time of the flash, about 2:00 p.m.). The travel time for the thunder was thus about 25 seconds.



To determine how far each seismograph is from an earthquake, students need to figure out how the arrival times at three seismograph stations can be applied to a graph that plots travel time versus distance from earthquake (Figure 4.6, p. 64). They then draw a circle on a map around each of the three seismograph stations with the radius determined from the graph. The epicenter is located at the point where the circles intersect. Younger students might use a graph that plots the difference in P and S arrival times instead of the travel times, making for a simpler problem. However, in either case, the values in the data sets given to the students (arrival times) do not directly correspond to what's plotted on the graph (either travel time or difference in travel times). When students try to chart the arrival times on the axis labeled "travel time" (or "difference in travel times"), they get nonsensical results, which forces them to go back and rethink what the graph means.

Figure 4.6

Graph of seismic wave travel times versus surface travel distance



Seismograph data provide arrival times for P and S waves from an earthquake. In figuring out how far each seismograph was from the earthquake, students need to realize that this graph does not plot arrival times, and adjust their strategy accordingly. They also need to realize that the difference in the travel times for the P and S waves and the difference in arrival times will be the same value.

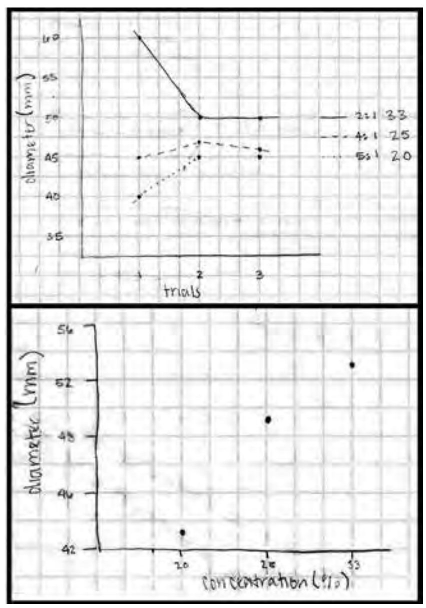
Another way to give students a chance to think about axis labels is to let them choose how to plot their own data. Unless specifically directed otherwise, students tend to gravitate toward histograms, rather than the *x-y* scatter plots that show the correlations between two experimental variables. Not specifically telling students what kind of graph to use can introduce an opportunity to talk about different kinds of graphs.

One year, I (Russ) had college students measure the effect of viscosity and eruption rate on the slope and diameter of sugar-water volcanoes on the distant (imaginary) planet of Lollipop. Students were asked to determine the relationship between volcano diameter and one of the following: composition of sugar water, eruption rate, or temperature.

Several groups chose to study the effect of melt composition (sugar acting as the proxy for silica concentration, which influences the viscosity of lava in volcanoes on Earth). Despite knowing the goal of the experiment, several groups didn't initially include with their report an *x-y* graph showing the variation in diameter with composition. One group plotted volcano diameter versus the trial number for three different trials of each of three compositions, making a line graph as in Figure 4.7. This graph provided useful information, just not the relationship between the dependent and independent variables the way a scatter plot would. For example, the graph showed the reproducibility of their results, giving a feel for experimental uncertainty, and offered a way to consider if there were any unexpected trends with time in their measurements. The freedom to plot a variety of graphs gave us the opportunity to talk about the value of different types of graphs.

Figure 4.7

Student graphs from an experimental investigation of the relationships between melt composition and volcano diameter (at fixed flow volumes, flow rates, and melt temperature) on the imaginary world of Lollipop



The results are reported for three melt compositions (by mass): 20% water and 80% sugar, 25% water and 75% sugar, and 33% water and 67% sugar. Volcano diameter was plotted against trial number in the upper graph—a type of line graph—rather than plotting melt composition versus diameter in an *x-y* scatter plot. This provided an opportunity to talk about the value of different types of graphs. After discussing, students plotted the average diameter against melt composition (lower graph), but the lower graph plots categorical data along the *x* axis, ordered by time of experiment, making it no different in concept from a histogram—notice that there is no meaningful scale on this graph; rather, the data are simply plotted against the three different compositions.

FINAL THOUGHTS

Reading a graph requires paying attention to the details of the graph, including what variables are plotted against each other, whether the variables are correlated, and the slope of that correlation. Most important, reading a graph requires paying attention to what the graph means in the real world. In science, graphs are not simply abstract numerical constructs. Graphs represent real phenomena, and understanding a graph requires visualizing the real-world meaning of it.

R. T. Rybak, a former mayor of Minneapolis, gave a presentation for the Minnesota Science Teachers Association in 2015. He recalled a story told by a colleague whose daughter taught math first in Los Angeles and then in Minnesota. She was surprised to find that her Minnesota students understood negative numbers much faster than her California students. Rybak associated that difference with Minnesota's cold winters, and the corresponding mental image Minnesota kids have of a thermometer scale that goes both above and below zero. In fair disclosure, we Minnesotans are always on the lookout for reasons to think well of our winters, so maybe we should take the story with a grain of salt, but the value in associating numbers with life experience remains sound.

We might call this life connection to numbers *experiential meaning.* Reading and constructing graphs requires that we connect the content of the graphs to experiential meaning. We need to think about how the graph—its slope, its values—relates to the world around us. We need to help our students do that.

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EXAMPLE ACTIVITY DESIGN

THE IMPACT-CRATERING EXPERIMENT

What to Graph, How to Graph It, and How to Make Predictions

The graphing activity we present here is a continuation of the experimental activity begun in Chapter 2. In Chapter 2, students identified questions to address, developed their experimental methods, made measurements, and organized their results into a table. Here we walk through how to coach students in analyzing and interpreting their experimental data using graphs.[C12]

TEACHER PREPARATION AND PLANNING

Look over the data your students derived from their cratering experiments. Make a graph or two of your own. Which are the independent and dependent variables? On which axes should they be plotted? Would it be better to combine some results onto a single plot? For example, you might plot drop height versus crater size for a variety of different masses or impactor size. Think about how you can encourage and guide your students as they construct their graphs without telling them exactly what to do. Think about any peculiarities in the students' data so you are ready to facilitate discussion when they discover differences between groups.

EXAMPLE PROMPTS AND LIMITING OPTIONS

Taking a Look at the Data

You might get students started analyzing results by asking them to look at their data, still in table form. For example, you might give the following prompts:

- Can you spot any consistent trends?
- What variables appear to affect crater size and in what way?
- Do the trends appear linear or nonlinear?
- Are the results reproducible within each group, meaning are data similar for multiple trials of the same variable?
- Are the results reproducible between the groups that tested the same variable?
- Are the results what you expected?

- Do the data make sense given the experimental observations and conditions?
- If there are differences in results between groups, can you identify possible reasons? For example, did someone measure in different units?

Preparing to Graph the Data

Talk about types of graphs and the kinds of data that are best plotted on them. In particular, talk about the difference between a bar graph (good for data that can be counted and put in bins) versus an *x-y* scatter plot (good for seeing correlations between two numerical variables). If students need a refresher on the mechanics of graphing, you can go through some simple examples. For example, you might ask students the following questions:

- Which axis do you want to plot the variables on?
- Do you want to do one graph with all your data, or more than one graph?
- What scale do you want to choose for each axis?

Note: We don't recommend using computer graphing routines, which choose the scales behind the scenes and make setting up the graph seem like magic, but if your goal is to also teach students how to use graphing software and you can spare the large upfront time to learn the technology, go for it.

Graphing the Data

Have students graph their own results first, then perhaps graph the data from another group that measured the same variables, plotting it on their own graph. This can help bring home the value of clear data table formulation that other people have to read. It also gives students an opportunity to recognize any differences in results between groups. You might also have groups plot the results for other variables measured by other groups. At this point, it's not necessary for students to draw any lines or "connect any dots" on their graphs.

Analyzing the Results

Remind students how to look for trends in their data. For example, you might ask the following questions:

- Does it make the most sense to "connect the dots" of the data, or does drawing a smooth line (or curve) of best fit through the data make the most sense?

- If you were to draw a line or curve through your data, would it be linear or nonlinear?
- Can you explain the meaning of the trends you see?
- What does the trend tell you about the relationship between crater size and the variables that affect it?

Help students explore the difference between one group's results and the results from another group who experimented with the same variables. Can they identify causes of the differences? Group members often respond to this kind of question by saying "we measured wrong." Encourage students to think beyond this simplistic response. Let groups show one another how they arrived at their measurements. Prompt students' discussions with these questions:

- Might someone have inadvertently introduced a new variable?
- Might differences in results be due to the coarseness of your measuring tools or differences in the way groups chose to do their measurements?

Help students develop a feel for the experimental uncertainty in their measurements. You might prompt them with these questions:

- Based on the scatter in your data, how reproducible are your results?
- Would a line or curve of best fit go exactly through each point, or would the line or curve take a path between points?
- What does this mean about the measured values?
- If there is a large amount of scatter compared with the overall trend, what does that mean for your confidence in the trend?
- If there is a lot of scatter in the data around a trend, what does that mean for your confidence in the exactness of the measured values?

The Big Challenge—Making a Prediction

Valid science makes predictions that can be shown to be either true or false. Discuss the idea that if their experiments show a causative relationship between variables, then they should be able to predict an outcome that was not directly tested in the experiments.

Tell students you are going to drop a ball of mass *X* from height *Y*. Give groups enough time to consider their graphs and data table and to write down their predictions for how big the new crater will be. You can do this for several different masses and drop heights.

We suggest considering only one variable at a time for any one prediction. For example, if a group varied the mass of impactors, not drop height, you would choose an impactor with a mass that is different from the ones the students used, but the same drop height. If a group varied drop height, but not mass, then choose a drop height different from their experimental ones but using the same mass. Maybe for one prediction you could mix it up by changing multiple variables and having them interpolate.

After each prediction, do the experiment two or three times and measure the crater diameter for each. Perhaps measure the crater diameter in two directions for each experiment. Calculate an average of the multiple measurements so students understand the idea that repeated measurements decrease uncertainty. Tell the students the results and direct them to compare the measured value with their predicted value. Discuss how close the predicted value needs to be to the measured value to still be counted as "right." For predictions that are way off, discuss possible explanations for the difference.

For scoring and grading, you might choose the "right" answer to be anything within 10% or even 20% of the predicted value. No one will ever predict the crater size exactly (you can't even measure it exactly). This provides another chance to discuss experimental uncertainty if you choose. You can give credit for the accuracy of their prediction, giving higher scores to those who are closer, say in increments of 10%, which gives the students some "skin in the game" when they make their predictions.

EXAMPLE INTERACTION

Student question: When I draw the line on the graph do I just connect the dots?

Teacher prompt: Do the dots fall exactly along a perfect line or curve?

Student observation: Well, sort of, but they kind of bounce around a bit. The dots don't really line up.

Teacher prompt: Do you think the not lining up reflects how velocity really affects the size of the crater?

Student interpretation: I think the bouncing around is probably because we didn't measure it exactly right.

Teacher prompt: Why do you think that?

Student reasoning: Well, we redid this one experiment and one measurement is higher and the other measurement is lower, so it doesn't seem like it's a real difference.

Teacher prompt: So do you think that connecting the dots gives you a better measure of how the real world behaves, or would a smooth curve do that?

Student conclusion: Probably the smooth curve.

SUMMARY CHECKLIST FOR TEACHER AS PRACTITIONER OF SCIENCE

- Plan time for students to discuss the meaning of their data *before* they start graphing.
- Review types of graphs and talk about how and what to plot, depending on students' background knowledge.
- After students graph their own data, plan for discussions on what the graphs and data mean in terms of what students experienced and observed during their experiments.
- Have students use graphed data to predict new impact crater sizes.
- Find some way to give students some skin in the game—for example, through grading or class challenges.

TEACHER REFLECTION

Consider ways to use your students' newly exercised graphing skills in future units and lessons. For example, you might have students sketch conceptual graphs given a basic understanding of natural variations. How will air volume change as the temperature of air increases; what will the graph look like, in concept? Or you might take graphical data from real research or something in the news and have students interpret what the graphed data are telling us.

Tie your students' experimental research to the big ideas and driving questions on which your curriculum is based. In what ways can your students' experimental analyses help them make sense of natural phenomena? For example, this cratering research project ties to our big idea that planets have a history of change; it also ties to the *NGSS* disciplinary core idea ESS1.C that we can learn about the history of our solar system by looking at asteroids, meteorites, and the cratered surfaces of other planetary bodies.

INDEX

Page numbers in **boldface** type refer to figures or tables.

Learning to Read the EARTH and Sky

Explorations Supporting the *NGSS*

GRADES 6–12

"*Learning to Read the Earth and Sky* is a wonderfully valuable book of background information, activities, historical and practical examples, and discussions of teaching. One particularly impressive feature is its presentation of science and engineering practices such as modeling and arguing from evidence. My recommendation: This is a book for your resource shelf."

—**Rodger W. Bybee**, author of *The BSCS 5E Instructional Model: Creating Teachable Moments* (NSTA Press, 2015)

If you have trouble getting students to take ownership of their earth science labs, it's time to refresh your approach. This book is the multifaceted resource you need to bring authentic science—and true engagement—into your classroom. It offers inspiration for reaching beyond prepared curricula, engaging in discovery along with your students, and using your lessons to support the *Next Generation Science Standards (NGSS).*

Three sections form the heart of the book:

1. **The Practices of Science:** Nine chapters help your students understand the basic tools and language of science, from proposing a question onward.
2. **The Language of the Earth:** Five chapters discuss reading the story of the Earth's past (written in rocks and layers of rock), figuring out the nature of places we can never visit (such as distant stars and the Earth's core), and tracking the movement of elements through the Earth's complex cycles and systems.
3. **YOU Can Do It!** Three chapters describe your role as an expert mentor and practitioner of science.

Learning to Read the Earth and Sky also provides refreshing guidance on how to translate the sweeping core ideas of the *NGSS* into specific examples students can touch, see, and experience. Become a fellow investigator with your students as you involve them in real questions whose answers are not pre-ordained by the curriculum. With this book, you'll help your students take ownership of their labs—not just follow a recipe.

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