PART I

Foundations

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CHAPTER 1

Student Engagement in Science and Engineering Practices

During my career as a secondary science teacher, teacher educator, and teacher education researcher, I set a primary goal of helping my students to learn how to learn. If they could become independent learners in class, then not only could they become efficient and effective learners in my science and science education courses, they could also transfer these skills to other topics. There is something powerful in being able to control your own learning, and it can open pathways to new skills and content knowledge that you never knew existed.

In order to help my students learn how to learn, I integrated into the disciplines of science and engineering a learning theory from educational psychology called self-regulated learning (SRL; Zimmerman, 2000). Self-regulated learning is a systematic method that looks at the way one learns, and the theory explains tangible processes that a learner uses to optimize their strategies. It has been shown over the years to be a very flexible theory, and has been used in many different subject matters and contexts such as writing, sports, science, and mathematics (Corno & Mandinach, 1983; Rohrkemper, 1989; Ryan, Connell, & Deci, 1984; Wang & Peverly, 1986; Zimmerman & Kitsantas, 2002). Self-regulated learning strategies have been taught to students to help them learn factual content knowledge, but there are other areas in which to support science and engineering students, namely, disciplinary approaches used while pursuing science and engineering (Duschl & Bybee, 2014; Pleasants & Olson, 2019).

Information about content knowledge of a subject is relatively easy to find on various platforms. However, defining and applying practices is more difficult. Understanding the role of practices and how to perform practices in the discipline allows a learner to gain a deeper level of knowledge, because a person can do science and engineering if they understand the practices. This gives them the power to find out relationships between variables on their own. Student understanding of science and engineering practices also goes hand in hand with self-regulated learning. Students who understand how to go about asking questions, developing procedures, gathering evidence, and communicating solutions can pursue problem-solving independently. The addition of SRL skills to the ability to perform science and engineering practices can result in students who can self-motivate, set productive goals, monitor their progress, and reflect on productive and unproductive processes. In effect, actively overlaying SRL onto learning about science and engineering practices can amplify the accuracy and efficiency of how students problem-solve while implementing disciplinary approaches.

The purpose of this book is to help teachers, teacher educators, and teacher education researchers establish and execute learning environments that support science and engineering students as self-directed learners. Teachers can use the ideas in the book to model and support student SRL, as well as to design explicit and reflective classrooms for students learning science and engineering practices. Teacher educators can use the ideas in the book to teach preservice teachers how to design learning environments that model, support, and assess student SRL and knowledge about science and engineering practices. Teacher education researchers can use the book to design research methodologies to investigate how teachers and students go about using SRL to learn science and engineering practices. The book directly addresses the teaching of primary and secondary students (aged 5–18) because that is what I have experienced in my career. However, the ideas in the book can be adjusted developmentally for undergraduate learners.

1.1 What Makes a Scientist a Scientist?

In order to self-regulate their learning, a student needs to have a context of learning about something, some skills or knowledge. Since this book is focused on science and engineering learning, it is important to know how science is defined as a discipline. In other words, what makes science a field of study? Science is treated separately from engineering here because they have different aims. A major aim of science is to explain phenomena that occur in the natural world. This is different from one of the major aims of engineering, to support human needs, which will be discussed in more detail in Section 1.2.

There has been a great deal of research on what makes science a unique discipline, often called the nature of science (NOS; Osborne et al., 2003). Within this research there are arguments about the level of detail to pursue in order to describe science as a discipline. For example, is science defined enough as a general discipline or should we be looking deeply into content areas such as biology, chemistry, and geology? An examination of standards of learning regarding NOS for all fifty states in the United States revealed that K-12 schools in the United States are treating science as a single, general discipline which is represented by overlapping aspects of NOS from various educational research frameworks (McComas, 2019). An applied approach to teaching NOS in K-12 classrooms would focus on the following overlapping aspects found in the standards:

- Science uses empirical evidence to make claims
- Scientific knowledge is mostly stable but tentative when new theories, models, and evidence are agreed upon
- History and societal norms influence knowledge production in science
- Science and technology have different aims, but support each other's development
- Scientists use creativity, critical reasoning, curiosity, and healthy skepticism in investigations
- Scientists work collaboratively and have professional standards that include ethical standards
- Scientific knowledge requires peer review

Although these aspects are important for all K-12 students to understand so that they can evaluate scientific claims and comprehend what is valued in scientific endeavors, the aspects tend to be philosophically oriented and may not be helpful in guiding students during investigations in a practical way.

Quality K-12 science instruction strives to mimic the ways scientists go about their investigations, but there are distinctions between the science students do in school and the science that professional scientists engage in (National Research Council, 1996). For example, professional scientists have a great deal of content knowledge and focus on specializations, whereas K-12 science students are generalists and are often learning each grade level's particular science knowledge for the first time. Although science students have life experience, they do not have the background knowledge that professional scientists possess. Professional scientists know their specialized field well and investigate questions about things that are currently murky, unknown, or on the fringes of the knowledge base. Students, on the other hand, usually investigate ideas that are accepted by the scientific community in order to understand them more thoroughly and build a base of knowledge in the field. Professional scientists differ from science students in that they share information globally by attending conferences and working in collaborative groups. Student scientists may be working in groups, but it is often for the purpose of developing communication skills, collaboration skills, and science content knowledge.

There are distinctions between professional science and school science, but there are also common aspects to both domains. The commonalities lie in science practices, approaches to investigations, or inquiries that exemplify habits of mind and methods that are valued by the discipline of science. As categorized by the Next Generation Science Standards (NGSS Lead States, 2013) in the United States, science practices are as follows:

- Asking questions
- Developing and using models
- Planning and carrying out investigations
- Analyzing and interpreting data
- Using mathematics and computational thinking
- Constructing explanations
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

Students may not have as much background knowledge or expertise as professional scientists but they can still perform science practices, such as asking scientific questions, developing and using models based on their growing baseline knowledge, and engaging in argument from evidence.

1.2 What Makes an Engineer an Engineer?

As in the field of science education, engineering educators have explained what makes engineering a unique discipline. Based on the Accreditation Board for Engineering and Technology (ABET, 2021) and the National Academy of Engineering and National Research Council report, *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* (2009), the nature of engineering can be described as what engineers do in the cyclical design process, how engineering impacts society, and how society impacts engineering. Topics in K-12 engineering education tend to emphasize engineering design, incorporating mathematics, science, and technology knowledge and skills, and promoting engineering habits of mind. Pleasants and Olson (2019) conducted a review of literature to develop a conceptual framework for the nature of engineering and found these disciplinary features:

- Design in engineering
- Specifications, constraints, and goals

- Sources of engineering knowledge
- Knowledge production in engineering
- The scope of engineering
- Models of design processes
- Cultural embeddedness of engineering
- The internal culture of engineering
- Engineering and science

Like NOS, the nature of engineering has strong conceptual foundations, but in order to be able to help students self-regulate their learning, the learning tasks need to be practical and observable. Self-regulated learning requires a learner to be able to set tangible goals, monitor those goals, and reflect on the outcome in relation to the goals. Again, a practical solution to teaching students to think like engineers is to focus on engineering practices. The Next Generation Science Standards have incorporated engineering practices into the standards that overlap with the science standards:

- Defining problems
- Developing and using models
- Planning and carrying out investigations
- Analyzing and interpreting data
- Using mathematics and computational thinking
- Designing solutions
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

Science and engineering practices both depend on iterative cycles of inquiry that are governed by rational and logical thinking that lead to valid information. Science practices can guide students to understanding the natural world. Engineering practices can guide students to solving human needs. When students master science and engineering practices, they have a framework for problem-solving in many different contexts and develop the ability to refine their skills through conducting investigations.

1.3 Content, Procedural, and Epistemic Knowledge

As described earlier, professional scientists and engineers possess a great deal of background knowledge. This background knowledge is not only about content, but it is also about methods, practices, and rationales. Science and engineering practices are difficult to learn in a vacuum and require some content knowledge as a foundation, as well as knowledge of the rationale for using a practice in a particular situation. These three types of knowledge are known as content knowledge, procedural knowledge, and epistemic knowledge. Content knowledge includes the body of factual knowledge known as a discipline (e.g. science, mathematics, and engineering). Procedural knowledge is the understanding of how something is accomplished (e.g. science and engineering practices). Epistemic knowledge is understanding how an expert in a discipline thinks and what is valued in the discipline (e.g. NOS to nature of science). All three types of knowledge are important to learn so that one has flexibility and expertise in that type of disciplinary thinking (Osborne, 2014). A learner could learn about content knowledge alone, but it amounts to a collection of trivial facts. A learner could learn about procedural knowledge alone, but without content knowledge, it would be like steps of a process that have no goal. Learning about content and procedural knowledge without epistemic knowledge can result in a learner robotically performing practices to learn content but with no disciplinary guidance. All three types of knowledge are required to truly understand a discipline.

This book is structured so that teachers can address all three types of knowledge. Teacher educators and teacher education researchers can use the book to help teachers structure learning environments so that students understand how to think like a scientist and an engineer (epistemic knowledge) through understanding how science and engineering practices are performed (procedural knowledge). Content knowledge is addressed to a lesser extent, but is still present in the application of design challenges and investigations throughout the second part of the book.

1.4 Practices as a Lynchpin for Connecting Content and Epistemic Knowledge

Content, procedural, and epistemic knowledge all have their role in developing well-rounded learners. Self-regulated learning has shown to be helpful in supporting student learning of content knowledge (DiBenedetto & Zimmerman, 2010; Peters, 2012), epistemic knowledge (Peters & Kitsantas, 2010), and procedural knowledge in the form of science and engineering practices (NGSS Lead States, 2013). The focus of this book is on science and engineering practices because they can be the lynchpin for connecting content, epistemic, and procedural knowledge.

As demonstrated in Figure 1.1, there is a bi-directional relationship between content knowledge and science and engineering practices, and between epistemic knowledge and science and engineering practices. Students ask questions, set up investigations, analyze data, and communicate results (procedural knowledge) that can elaborate their current content knowledge. Conversely, prior content knowledge about the phenomena being investigated helps a science and engineering student effectively focus their use of practices. The outcomes of the practices can demonstrate disciplinary knowledge of science and engineering, particularly if the student is explicitly monitoring the ways the practices are being followed (e.g. systematically). Epistemic ideas can also help students direct their practices toward a particular goal, such as extending knowledge or solving a problem for a human need.

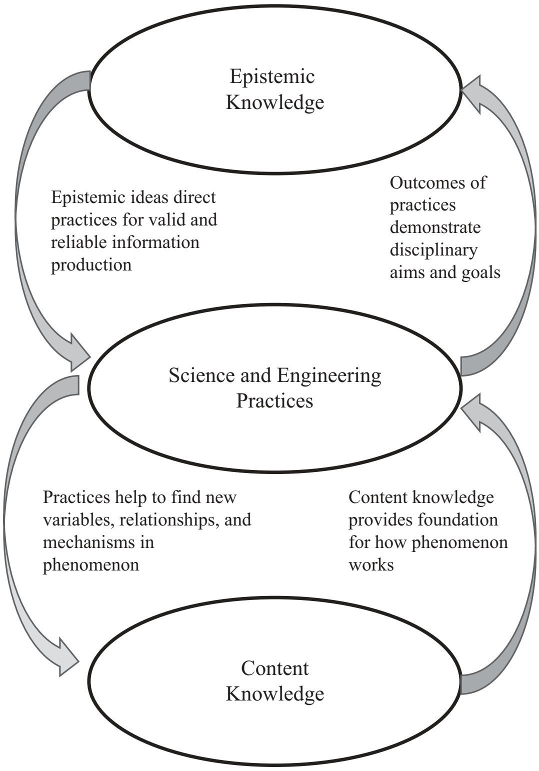

Figure 1.1 Relationship of science and engineering practices with content and epistemic knowledge

Consider the following scenario as an example. Celia is a student who understands the functionality of simple circuits and who is proficient in science and engineering practices. She is beginning an investigation that examines the question: How are parallel circuits different from simple circuits? Celia's content knowledge about simple circuits consists of the following facts:

- Simple circuits have a power source, a resistor such as a lamp, and one loop of conducting material
- The power must be strong enough and the loop must be complete and closed for the lamp to light

Celia is presented with a parallel circuit that has two branches, one power source and two lamps. She applies her content knowledge about simple circuits and notices that there is more than one loop in the parallel circuit. She can then focus her procedure design for the investigation on how the circuit behaves when each lamp is taken out of the circuit. Her content knowledge provides the foundation for how the phenomena might work and which variables she can manipulate to help her answer the research question. Once she tries to take out one lamp, her epistemic understanding that all conditions should be tested helps her to create more complete procedures. Once she has completed the investigation, she can reflect on how she used valid procedures in her investigation that can refine her epistemic knowledge. Celia's content, procedural, and epistemic knowledge allowed her to look at the investigation from multiple perspectives. The addition of explicit self-regulated learning processes could help develop her knowledge in a more systematic way.

1.5 Relationship of Self-Regulated Learning to Science and Engineering Practices

Self-regulated learning is inherently a problem-solving process. As explained in Chapter 3, the processes in the cyclical phases of SRL are essentially variables in a learner's toolkit, which can be measured and manipulated to change learning outcomes. SRL has three phases that occur (a) when a learner prepares for the learning task, (b) when a learner performs a learning task, and (c) when a learner evaluates the outcome of learning and adapts as needed. A cycle of SRL has parallels to both scientific inquiry and the engineering design processes. Chapter 3 goes into further detail regarding the processes that are associated in each phase of SRL and how they parallel different science and engineering practices.

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When a student is more aware of their learning processes, they can treat the process of learning as a science investigation or engineering problem, thus reinforcing their understanding of science and engineering practices while improving their learning processes.

1.6 Structure of the Book

The book is structured into three main parts: (a) *Foundations*, (b) *Engaging in Disciplinary Tasks in Science and Engineering*, and (c) *Educational Research and Teacher Education Applications*. This book is written so that you can treat the book as a user manual rather than needing to read the book cover to cover, although that is also an option. If a reader is interested in supporting students on a particular practice such as asking questions and designing solutions with self-regulated learning, they can read Chapter 4 for background and strategies for that particular practice. However, if the reader is not familiar with self-regulated learning, they may want to read Chapter 3 before proceeding to the chapters on application of SRL theory to the practices. Likewise, if a reader is unfamiliar with the practices, they may want to read Chapter 2 before moving on.

The *Foundations* part includes chapters that discuss background ideas in science and engineering practices, self-regulated learning, and explains the overlap between the two realms. The *Engaging in Disciplinary Tasks in Science and Engineering* part has chapters that are dedicated to each science and engineering practice. In this part of the book, the chapters are organized by the practices found in the Next Generation Science Standards. Each of the chapters analyze the practice and articulate the skills that comprise the practices beyond what is available in the standards documents. From the detailed analysis of the practices, the chapters explain a way to help students self-regulate their knowledge of the skills that make up the practice, provide a positive and a negative case study of the practice, and offer questions for teachers to consider in order to adapt ideas for their classroom.

The *Educational Research and Teacher Education Applications* part of the book provides ideas for professional development designs based on a review of the research for preservice and inservice teachers in elementary and secondary settings. This part also describes example lessons using the 5E lesson planning format that embeds self-regulated learning. Finally, this part offers qualitative, quantitative, and mixed-methods research designs for studying student engagement in science and engineering practices supported by self-regulated learning.