Argument-Driven Inquiry in PHYSICS

VOLUME 1

MECHANICS LAB INVESTIGATIONS for GRADES 9–12

Victor Sampson, Todd L. Hutner, Daniel FitzPatrick,
Adam LaMee, and Jonathon Grooms

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Argument-Driven Inquiry

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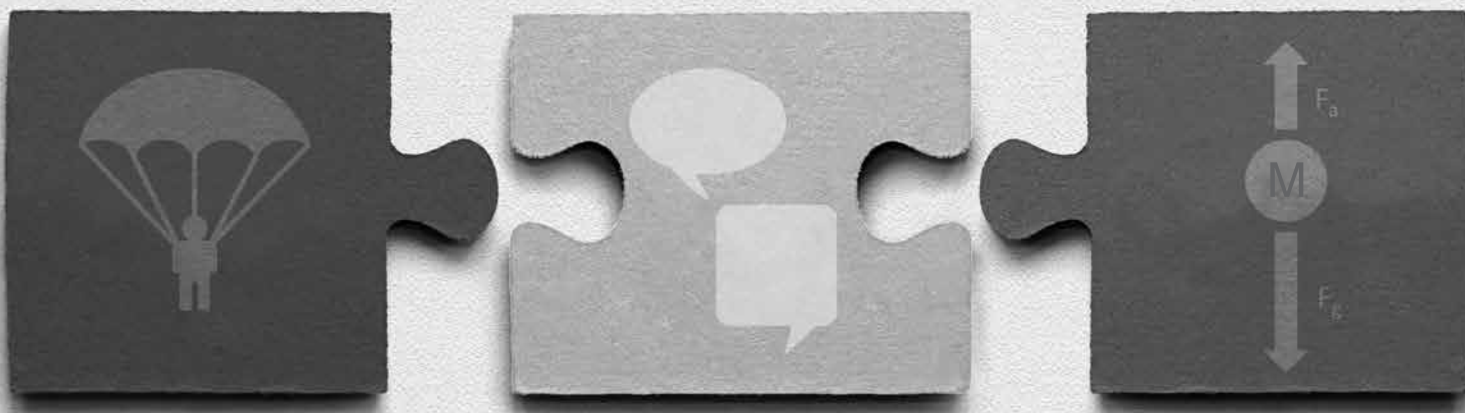

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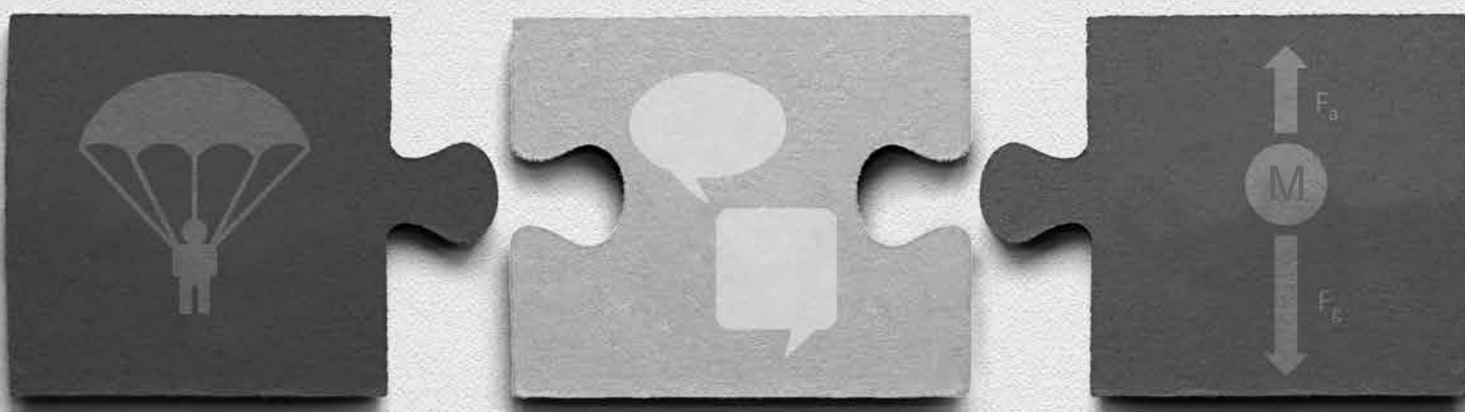

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PREFACE

A Framework for K–12 Science Education (NRC 2012; henceforth referred to as the *Framework*) and the *Next Generation Science Standards* (NGSS Lead States 2013; henceforth referred to as the *NGSS*) call for a different way of thinking about why we teach science and what we expect students to know by the time they graduate high school. As to why we teach science, these documents emphasize that schools need to

> ensure by the end of 12th grade, *all* students have some appreciation of the beauty and wonder of science; possess sufficient knowledge of science and engineering to engage in public discussions on related issues; are careful consumers of scientific and technological information related to their everyday lives; are able to continue to learn about science outside school; and have the skills to enter careers of their choice, including (but not limited to) careers in science, engineering, and technology. (NRC 2012, p. 1)

The *Framework* and the *NGSS* are based on the idea that students need to learn science because it helps them understand how the natural world works, because citizens are required to use scientific ideas to inform both individual choices and collective choices as members of a modern democratic society, and because economic opportunity is increasingly tied to the ability to use scientific ideas, processes, and habits of mind. From this perspective, it is important to learn science because it enables people to figure things out or solve problems.

These two documents also call for a reappraisal of what students need to know and be able to do by time they graduate from high school. Instead of teaching with the goal of helping students remember facts, concepts, and terms, science teachers are now charged with the goal of helping their students become *proficient* in science. To be considered proficient in science, the *Framework* suggests that students need to understand four disciplinary core ideas (DCIs) in the physical sciences,[1] be able to use seven crosscutting concepts (CCs) that span the various disciplines of science, and learn how to participate in eight fundamental scientific and engineering practices (SEPs; called science and engineering practices in the *NGSS*). The DCIs are key organizing principles that have broad explanatory power within a discipline. Scientists use these ideas to explain the natural world. The CCs are ideas that are used across disciplines. These concepts provide a framework or a lens that people can use to explore natural phenomena. These concepts, as a result, often influence what people focus on or pay attention to when they attempt to understand how something works or why something happens. The SEPs are the different activities that scientists and engineers engage in as they attempt to generate new concepts, models, theories, or laws that are both valid and reliable. All three of these dimensions of science are important. Students need to not only know about the DCIs, CCs, and SEPs but also

1 Throughout this book, we use the term *physical sciences* when referring to the disciplinary core ideas of the *Framework* (in this context the term refers to a broad collection of scientific fields), but we use the term *physics* when referring to courses at the high school level (as in the title of the book).

must be able to use all three dimensions at the same time to figure things out or to solve problems. These important DCIs, CCs, and SEPs are summarized in Figure 1.

FIGURE 1

The three dimensions of science in *A Framework for K–12 Science Education* and the *Next Generation Science Standards*

Science and engineering practices	Crosscutting concepts
1. Asking Questions and Defining Problems	1. Patterns
2. Developing and Using Models	2. Cause and Effect: Mechanism and Explanation
3. Planning and Carrying Out Investigations	3. Scale, Proportion, and Quantity
4. Analyzing and Interpreting Data	4. Systems and System Models
5. Using Mathematics and Computational Thinking	5. Energy and Matter: Flows, Cycles, and Conservation
6. Constructing Explanations and Designing Solutions	6. Structure and Function
7. Engaging in Argument From Evidence	7. Stability and Change
8. Obtaining, Evaluating, and Communicating Information	

Disciplinary core ideas for the physical sciences*
• PS1: Matter and Its Interactions
• PS2: Motion and Stability: Forces and Interactions
• PS3: Energy
• PS4: Waves and Their Applications in Technologies for Information Transfer

* These disciplinary core ideas represent one of the four subject areas in the *Framework* and the *NGSS;* the other subject areas are life sciences, earth and space sciences, and engineering, technology, and applications of science.

Source: Adapted from NRC 2012 and NGSS Lead States 2013.

To help students become proficient in science in ways described by the National Research Council in the *Framework,* teachers will need to use new instructional approaches that give students an opportunity to use the three dimensions of science to explain natural phenomena or develop novel solutions to problems. This is important because traditional instructional approaches, which were designed to help students "learn about" the concepts, theories, and laws of science rather than how to "figure out" how or why things work, were not created to foster the development of science proficiency inside the classroom. To help teachers make this instructional shift, this book provides 23 laboratory investigations designed using an innovative approach to lab instruction called argument-driven inquiry (ADI). This approach is designed to promote and support three-dimensional instruction inside classrooms because it gives students an opportunity to use DCIs, CCs, and SEPs to construct and critique claims about how things work or why things happen. The lab activities described in this book will also enable students to develop the disciplinary-based literacy skills outlined in the *Common Core State Standards* for English language arts (NGAC and CCSSO 2010) because ADI gives students an opportunity to give presentations to their peers, respond to audience questions and critiques, and then write, evaluate, and revise reports as part of each lab. Use of these labs, as a result, can help teachers align their teaching with current recommendations for improving classroom instruction in science and for making physics more meaningful for students.

The labs included in this book all focus on the topic of mechanics. Thus, these labs focus on only two of the four physical sciences DCIs from the *NGSS* that are outlined in Figure 1. These two DCIs are Motion and Stability: Forces and Interactions (PS2) and Energy (PS3). The other two DCIs for physical sciences from the *NGSS* are a focus of other books in the ADI series. All the labs, however, are well aligned with at least two of the seven CCs and seven of the eight SEPs. In addition, the labs in this book are well aligned with the big ideas and science practices for Advanced Placement (AP) Physics 1, 2, and C: Mechanics (see Figure 2). These labs, as a result, can be used in a wide range of physics courses, including, but not limited to, a conceptual physics course for 9th or 10th graders that is aligned with the *NGSS*, an introductory physics course for juniors or seniors, or even an AP Physics 1, 2, or C: Mechanics course.

FIGURE 2

Selected big ideas and science practices for AP Physics 1 and 2 and the content areas and laboratory objectives for AP Physics C: Mechanics

AP Physics 1 and 2 big ideas	AP Physics 1 and 2 science practices
• Objects and systems have properties such as mass and charge. Systems may have internal structure. • Fields existing in space can be used to explain interactions. • The interactions of an object with other objects can be described by forces. • Interactions between systems can result in changes in those systems. • Changes that occur as a result of interactions are constrained by conservation laws.	1. Use representations and models to communicate scientific phenomena and solve scientific problems. 2. Use mathematics appropriately. 3. Engage in scientific questioning to extend thinking or to guide investigations. 4. Plan and implement data collection strategies in relation to a particular scientific question. 5. Perform data analysis and evaluation of evidence. 6. Work with scientific explanations and theories. 7. Connect and relate knowledge across various scales, concepts, and representations in and across domains.

Continued

FIGURE 2 (*continued*)

AP Physics C: Mechanics content areas	AP Physics C: Mechanics laboratory objectives
• Kinematics • Newton's laws of motion • Work, energy, and power • Systems of particles and linear momentum • Circular motion and rotation • Oscillations and gravitation	1. Design experiments 2. Observe and measure real phenomena 3. Analyze data 4. Analyze errors 5. Communicate results

Source: Adapted from *http://apcentral.collegeboard.com/apc/public/courses/teachers_corner/2262.html* (for AP Physics 1); *http://apcentral.collegeboard.com/apc/public/courses/teachers_corner/225113.html* (for AP Physics 2); *http://apcentral.collegeboard.com/apc/public/courses/teachers_corner/2264.html* (for AP Physics C: Mechanics).

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INTRODUCTION

The Importance of Helping Students Become Proficient in Science

The current aim of science education in the United States is for *all* students to become proficient in science by the time they finish high school. *Science proficiency*, as defined by Duschl, Schweingruber, and Shouse (2007), consists of four interrelated aspects. First, it requires an individual to know important scientific explanations about the natural world, to be able to use these explanations to solve problems, and to be able to understand new explanations when they are introduced to the individual. Second, it requires an individual to be able to generate and evaluate scientific explanations and scientific arguments. Third, it requires an individual to understand the nature of scientific knowledge and how scientific knowledge develops over time. Finally, and perhaps most important, an individual who is proficient in science should be able to participate in scientific practices (such as planning and carrying out investigations, analyzing and interpreting data, and arguing from evidence) and communicate in a manner that is consistent with the norms of the scientific community. These four aspects of science proficiency include the knowledge and skills that all people need to have in order to be able to pursue a degree in science, be prepared for a science-related career, and participate in a democracy as an informed citizen.

This view of science proficiency serves as the foundation for the *Framework* (NRC 2012) and the *NGSS* (NGSS Lead States 2013). Unfortunately, our educational system was not designed to help students become proficient in science. As noted in the *Framework*,

> K–12 science education in the United States fails to [promote the development of science proficiency], in part because it is not organized systematically across multiple years of school, emphasizes discrete facts with a focus on breadth over depth, and does not provide students with engaging opportunities to experience how science is actually done. (p. 1)

Our current science education system, in other words, was never designed to give students an opportunity to learn how to use scientific explanations to solve problems, generate or evaluate scientific explanations and arguments, or participate in the practices of science. Our current system was designed to help students learn facts, vocabulary, and basic process skills because many people think that students need a strong foundation in the basics to be successful later in school or in a future career. This vision of science education defines *rigor* as covering more topics and *learning* as the simple acquisition of new ideas or skills.

Our views about what counts as rigor, therefore, must change to promote and support the development of science proficiency. Instead of using the number of different topics covered in a course as a way to measure rigor in our schools, we must start to measure rigor in terms of the number of opportunities students have to use the ideas of science as a way to make sense of the world around them. Students, in other words, should be expected to learn how to use the core ideas of science as conceptual tools to plan and carry out investigations, develop and evaluate explanations, and question how we know what we know. A rigorous course, as result, would be one where students are expected to do science, not just learn about science.

Our views about what learning is and how it happens must also change to promote and support the development of science proficiency. Rather then viewing learning as a simple process where people accumulate more information over time, learning needs to be viewed as a personal and social process that involves "people entering into a different way of thinking about and explaining the natural world; becoming socialized to a greater or lesser extent into the practices of the scientific community with its particular purposes, ways of seeing, and ways of supporting its knowledge claims" (Driver et al. 1994, p. 8). Learning, from this perspective, requires a person to be exposed to the language, the concepts, and the practices of science that make science different from other ways of knowing. This process requires input and guidance about "what counts" from people who are familiar with the goals of science, the norms of science, and the ways things are done in science. Thus, learning is dependent on supportive and informative interactions with others.

Over time, people will begin to appropriate and use the language, the concepts, and the practices of science as their own when they see how valuable they are as a way to accomplish their own goals. Learning thus involves seeing new ideas and ways of doing things, trying out these new ideas and practices, and adopting them when they are useful. This entire process, however, can only happen if teachers provide students with multiple opportunities to use scientific ideas to solve problems, to generate or evaluate scientific explanations and arguments, and to participate in the practices of science inside the classroom. This is important because students must have a supportive and educative environment to try out new ideas and practices, make mistakes, and refine what they know and what they do before they are able to adopt the language, the concepts, and the practices of science as their own.

A New Approach to Teaching Science

We need to use different instructional approaches to create a supportive and educative environment that will enable students to learn the knowledge and skills they need to become proficient in science. These new instructional approaches will need to give students an opportunity to learn how to "figure out" how things work or why things happen. Rather than simply encouraging students to learn about the facts, concepts, theories, and laws of science, we need to give students more opportunities to develop explanations for natural phenomena and design solutions to problems.

This emphasis on "figuring things out" instead of "learning about things" represents a big change in the way we will need to teach science at all grade levels. To figure out how things work or why things happen in a way that is consistent with how science is actually done, students must do more than hands-on activities. Students must learn how to use disciplinary core ideas (DCIs), crosscutting concepts (CCs), and science and engineering practices (SEPs) to develop explanations and solve problems (NGSS Lead States 2013; NRC 2012).

A DCI is a scientific idea that is central to understanding a variety of natural phenomena. An example of a DCI in physics is the force of gravity, which is a type of interaction that occurs between objects with mass. This DCI not only explains the motion of planets around the Sun but also the motion of a rock dropped from a bridge.

CCs are those concepts that are important across the disciplines of science; there are similarities and differences in the treatment of the CC in each discipline. The CCs can be used as a lens to help people think about what to focus on or pay attention to during an investigation. For example, one of the CCs from the *Framework* is Energy and Matter: Flows, Cycles, and Conservation. This CC is important in many different fields of study, including but not limited to mechanics, thermodynamics, electricity and magnetism, and nuclear physics. This CC is equally important in biology; biologists use this CC to explore topics such as cellular processes, growth and development, and ecosystems. It is important to highlight the centrality of this idea, and other CCs, for students as we teach the subject-specific DCIs.

SEPs describe what scientists do to investigate the natural world. The practices outlined in the *Framework* and the *NGSS* explain and extend what is meant by *inquiry* in science and the wide range of activities that scientists engage in as they attempt to generate and validate new ideas. Students engage in practices to build, deepen, and apply their knowledge of DCIs and CCs. The SEPs include familiar aspects of inquiry, including such activities as Asking Questions and Defining Problems, Planning and Carrying Out Investigations, and Analyzing and Interpreting Data. More important, however, the SEPs include other activities that are at the core of doing science. These activities include Developing and Using Models, Constructing Explanations and Designing Solutions, Engaging in Argument From Evidence, and Obtaining, Evaluating, and Communicating Information. All of these SEPs are important to learn, because there is no single scientific method that all scientists must follow; scientists engage in different practices, at different times, and in different orders depending on what they are studying and what they are trying to accomplish at that point in time.

This focus on students using DCIs, CCs, and SEPs during a lesson is called *three-dimensional instruction* because students have an opportunity to use all three dimensions of science to understand how something works, to explain why something happens, or to develop a novel solution to a problem. When teachers use three-dimensional instruction inside their classrooms, they encourage students to develop or use conceptual models, design investigations, develop explanations, share and critique ideas, and argue from evidence, all of which allow students to develop the knowledge and skills they need to be proficient in science (NRC 2012). Current research suggests that all students benefit from three-dimensional instruction because it gives all students more voice and choice during a lesson and it makes the learning process inside the classroom more active and inclusive (NRC 2012).

We think the school science laboratory is the perfect place to integrate three-dimensional instruction into the science curriculum. Well-designed lab activities can provide opportunities for students to participate in an extended investigation where they can not only use one or more DCIs to understand how something works, to explain why something happens, or to develop a novel solution to a problem but also use several different CCs and SEPs during the same lesson. For example, a teacher can give students an opportunity to explore the motion of several different balls as they roll down a ramp. The teacher can then encourage them to use Newton's second law of motion (part of the DCI Motion and Stability: Forces and Interactions) and their understanding of (a) Cause and Effect: Mechanism and Explanation and (b) Scale, Proportion, and Quantity (two different CCs) to plan and carry out an investigation to figure out how the net force acting on a ball of a given mass affects its acceleration. During this investigation they must collect, analyze, and interpret data; use mathematics; construct explanations; argue from evidence; and obtain, evaluate, and communicate information (tasks that involve six different SEPs). Using multiple DCIs, CCs, and SEPs at the same time is important because it creates a classroom experience that parallels how science is done. This, in turn, gives all students who participate in a school science laboratory an opportunity to deepen their understanding of what it means to do science and to develop science-related identities. In the following section, we will describe how to promote and support the development of science proficiency during school science laboratories through three-dimensional instruction.

How School Science Laboratories Can Help Foster the Development of Science Proficiency Through Three-Dimensional Instruction

School science laboratory experiences[1] tend to follow a similar format in most U.S. science classrooms (Hofstein and Lunetta 2004; NRC 2005). This format begins with the teacher introducing students to an important concept or principle through direct instruction, usually by giving a lecture about it or by assigning a chapter from a

1 *School science laboratory experiences* are defined as "an opportunity for students to interact directly with the material world using the tools, data collection techniques, models, and theories of science" (NRC 2005, p. 3).

textbook to read. This portion of instruction often takes several class periods. Next, the students will complete a hands-on laboratory activity. The purpose of the hands-on activity is help students understand a concept or principle that was introduced to the students earlier. To ensure that students "get the right result" during the lab and that the lab actually illustrates, confirms, or verifies the target concept or principle, the teacher usually provides students with a step-by-step procedure to follow and a data table to fill out. Students are then asked to answer a set of analysis questions to ensure that everyone "reaches the right conclusion" based on the data they collected during the lab. The laboratory experience then ends with the teacher going over what the students should have done during the lab, what they should have observed, and what answers they should have given in response to the analysis questions, to ensure that the students "learned what they were supposed have learned" from the hands-on activity. This final step of the laboratory experience is usually done, once again, through whole-class direct instruction.

Recent research, however, suggests that this type of approach to laboratory instruction does little to help students learn key concepts. The National Research Council (2005, p. 5), for example, conducted a synthesis of several different studies that examined what students learn from laboratory instruction and found that "research focused on the goal of student mastery of subject matter indicates that typical laboratory experiences are no more or less effective than other forms of science instruction (such as reading, lectures, or discussion)." This finding is troubling because, as noted earlier, the main goal of this type of lab experience is to help students understand an important concept or principle by giving them a hands-on and concrete experience with it. In addition, this type of laboratory experience does little to help students learn how plan and carry out investigations or analyze and interpret data, because students have no voice or choice during the activity. Students are expected to simply follow a set of directions rather than having to think about what data they will collect, how they will collect it, and what they will need to do to analyze it once they have it. These types of activities also can lead to misunderstanding about the nature of scientific knowledge and how this knowledge is developed over time, because of the emphasis on following procedure and getting the right results. These "cookbook" labs, as a result, do not reflect how science is done at all.

Over the last decade, many teachers have changed their labs to be inquiry-based in order to address the many shortcomings of typical cookbook lab activities. Inquiry-based lab experiences that are consistent with the definition of *inquiry* found in the *National Science Education Standards* (NRC 1996) and *Inquiry and the National Science Education Standards* (NRC 2000) share five key features:

1. These labs are designed so students need to answer a scientifically oriented

question by conducting an investigation.

2. These labs give students an opportunity to develop their own method to collect data during the investigation.
3. Students are expected to formulate an answer to the question based on their analysis of the data they collected.
4. Students connect their answer to some theory, model, or law; this is the aspect of inquiry-based instruction that students tend to struggle with most.
5. Students are given an opportunity to communicate and justify their answer to the question.

These types of labs tend to be used by teachers as a way to introduce students to important content and to give students an opportunity to learn how to collect and analyze data in science (NRC 2012).

Although inquiry-based approaches give students much more voice and choice during a lab, especially when compared with more typical cookbook approaches, they do not do as much as they could do to promote the development of science proficiency. Teachers tend to use inquiry-based labs as a way to help students learn about new ideas rather than as a way to help students learn how to figure out how things work or why they happen. Students, as a result, rarely have an opportunity to learn how to use DCIs, CCs, and SEPs to develop explanations or solve problems. In addition, inquiry-based approaches rarely give students an opportunity to participate in the full range of scientific practices. Inquiry-based labs tend to be designed so students have many opportunities to learn how to ask questions, plan and carry out investigations, and analyze and interpret data but few opportunities to learn how to participate in the practices that focus on how new ideas are developed, shared, refined, and eventually validated within the scientific community. These important practices include developing models, constructing explanations, arguing from evidence, and obtaining, evaluating, and communicating information (Duschl, Schweingruber, and Shouse 2007; NRC 2005). Inquiry-based labs also do not give students an opportunity to improve their science-specific literacy skills. Students are rarely expected to read, write, and speak in a scientific manner because the focus of these labs is learning about content and how to collect and analyze data in science, not how to propose, critique, and revise ideas.

Changing the focus and nature of inquiry-based labs so they are more consistent with three-dimensional instruction can help address these issues. To implement such a change, teachers will not only have to focus on using DCIs, CCs and SEPs but will also need to emphasize "how we know" in the physical sciences (i.e., how new knowledge is generated and validated) equally with "what we know" about forces, motion, and energy (i.e., the theories, laws, and unifying concepts). We have found that this shift in focus is best accomplished by making the practice of arguing from evidence or scientific argumentation the central feature of all laboratory activities. We define *scientific argumentation* as the process of proposing, supporting, evaluating, and refining claims based on evidence (Sampson, Grooms, and Walker, 2011). The *Framework* (NRC 2012) provides a good description of the role argumentation plays in science:

> Scientists and engineers use evidence-based argumentation to make the case for their ideas, whether involving new theories or designs, novel ways of collecting data, or interpretations of evidence. They and their peers then attempt to identify weaknesses and limitations in the argument, with the ultimate goal of refining and improving the explanation or design. (p. 46)

When teachers make the practice of arguing from evidence the central focus of lab activities, students have more opportunities to learn how to construct and support scientific knowledge claims through argument (NRC 2012). Students also have more opportunities to learn how to evaluate the claims and arguments made by others. Students, as a result, learn how to read, write, and speak in a scientific manner because they need to be able to propose and support their claims when they share them and evaluate, challenge, and refine the claims made by others.

We developed the argument-driven inquiry (ADI) instructional model (Sampson and Gleim 2009; Sampson, Grooms, and Walker 2009, 2011) as a way to change the focus and nature of labs so they are consistent with three-dimensional instruction. ADI gives students an opportunity to learn how to use DCIs, CCs, and SEPs to figure out how things work or why things happen. This instructional approach also places scientific argumentation as the central feature of all laboratory activities. ADI lab investigations, as a result, make lab activities more authentic and educative for students and thus help teachers promote and support the development of science proficiency. This instructional model reflects current research about how people learn science (NRC 1999, 2005, 2008, 2012) and is also based on what is known about how to engage students in argumentation and other important scientific practices (Erduran and Jimenez-Aleixandre 2008; McNeill and Krajcik 2008; Osborne, Erduran, and Simon 2004; Sampson and Clark 2008). We will explain the stages of ADI and how each stage works in Chapter 1.

How to Use This Book

The intended audience of this book is primarily practicing high school physics teachers. We recognize that physics teachers teach many different types of physics courses. Some courses are conceptual in nature, some are algebra based, and some are calculus based. We understand how teaching these different types of physics courses results in different challenges and needs. We have therefore designed the laboratory investigations included in this book to meet the needs of teachers who teach a wide range of courses. Some labs, for example, require students to determine a general relationship or trend and do not require a lot of mathematics. These labs can be used in a physics course that is more conceptual in nature. Other labs, in contrast, require students to develop a mathematical model that students can use to explain and predict the motion of an object over time. These labs are intended for students in Advanced Placement (AP) Physics C: Mechanics who are concurrently enrolled in or have successfully completed an introductory calculus course. The majority of the labs, however, were written for an algebra-based physics course. These labs require some algebra, such as determining a mathematical relationship between two variables (which is often, but not always, a linear relationship). All of the labs were designed to give students an opportunity to learn how to use DCIs, CCS, and SEPs to figure things out.

As we wrote the labs for this book, we kept in mind the fact that physics is often a two-year program of study in many school districts. Students, as a result, often take Physics I in their 11th-grade year along with Algebra II and then take either AP Physics 1, AP Physics 2, or AP Physics C: Mechanics along with either AP Statistics or AP Calculus. We have therefore aligned the labs with the *NGSS* performance expectations (where applicable) and the AP Physics 1 and AP Physics C: Mechanics learning objectives so teachers can use these labs in either an introductory physics course or an AP physics course. We believe that it is important to focus on three-dimensional instruction in both contexts because students need to learn how to use DCIs, CCs, and SEPs to figure out how things work or why things happen even when they are taking AP physics. Lab instruction is also a major component of the AP physics curriculum. In AP Physics 1 and AP Physics C: Mechanics, for example, the College Board recommends that at least 25% of instructional time be devoted to laboratory experiences. These experiences should therefore do more than demonstrate, illustrate, or verify a target concept; they should promote and support the development of the four aspects of science proficiency.

One of the recent advances in physics education has been the development of physics-specific equipment that students can use during investigations; probeware and video cameras for collecting data; and data analysis software, including video analysis software, which enables students to explore the data they collect during an investigation. We recognize that while some physics teachers work in settings where this equipment is readily available and funds are easily accessed to purchase additional equipment, many others do not work in such settings. To address this concern, we have designed many of the labs in this book so they can be conducted in lower-tech ways, by using stopwatches and metersticks. Sometimes, however, a lab may not be worth doing if students do not have access to specific equipment such as a video camera and video analysis software. When materials are optional, we indicate in the Lab Handout that students “may also consider using” optional equipment. If this equipment is not available to you, when introducing the lab just let students know that they do not have the option to use that equipment. We also recognize that the initial cost to purchase the necessary equipment may be high, especially when compared with equipment needed for a chemistry or biology course. However, the replacement costs for these labs are minimal because the equipment should last several years; in contrast, biology or chemistry courses may require annual replacement of chemicals or specimens.

Finally, we want to make clear that we do not expect teachers to use every lab in this book over the course of an academic year. We wrote this book to support the teaching of mechanics, which is a topic found in the first-semester curriculum of a physics course. Concepts included under the topic of mechanics include kinematics, dynamics, circular motion and rotation, oscillations, momentum, and energy. We suggest that teachers who use this book choose one (or two, at most) labs for each of the six major concepts.

There are two types of labs included in the book: (1) introduction labs and (2) application labs. An introduction lab should be used at the beginning of a unit. These labs often require little formal knowledge of the target concept before students begin the investigation. For example, the lab on free fall (Lab 2) is an introduction lab and does not require students to know about the acceleration due to gravity, but students are still expected to use a DCI (Motion and Stability: Forces and Interactions) and two CCs (Patterns, Stability and Change) to figure out the relationship between the mass of an object and its acceleration during free fall. After students complete the lab, teachers can move forward to formalize the laws and formulas related to acceleration due to gravity through other means of instruction.

Application labs, on the other hand, are designed to come at the end of a unit. The intent of these labs is give student an opportunity to apply their knowledge of a specific concept they learned about earlier in the course, along with their knowledge of DCIs and CCs, to a novel situation. For example, Lab 23 requires students to use their knowledge about conservation of energy and the relationship between energy and power to determine the horsepower of a remote control toy car.

Organization of This Book

This book is divided into eight sections. Section 1 includes two chapters: the first chapter describes the ADI instructional model, and the second chapter describes the development of the ADI lab investigations and an overview of what is included with each investigation. Sections 2–7 contain the 23 lab investigations. Each investigation includes three components:

- Teacher Notes, which provide information about the purpose of the lab and what teachers need to do to guide students through it.
- Lab Handout, which can be photocopied and given to students at the beginning of the lab. It provides the students with a phenomenon to investigate, a guiding question to answer, and an overview of the DCIs and CCs that students can use during the investigation.
- Checkout Questions, which can be photocopied and given to students at the conclusion of the lab activity as an optional assessment. The Checkout Questions consist of items that target students' understanding of the DCIs, the CCs, and the nature of scientific knowledge (NOSK) and the nature of scientific inquiry (NOSI) concepts addressed during the lab.

Section 8 consists of five appendixes:

- Appendix 1 contains several standards alignment matrixes that can be used to assist with curriculum or lesson planning.
- Appendix 2 provides an overview of the CCs and the NOSK and NOSI concepts that are a focus of the lab investigations. This information about the CCs and the NOSK and NOSI are included as a reference for teachers.
- Appendix 3 provides several options (in tabular format) for implementing an ADI investigation over multiple 50-minute class periods.
- Appendix 4 provides options for investigation proposals, which students can use as graphic organizers to plan an investigation. The proposals can be photocopied and given to students during the lab.
- Appendix 5 provides a peer-review guide and teacher scoring rubric, which can also be photocopied and given to students.

Safety Practices in the Science Laboratory

It is important for all of us to do what we can to make school science laboratory experiences safer for everyone in the classroom. We recommend four important guidelines to follow. First, we need to have proper safety equipment such as, but not limited to, fume hoods, fire extinguishers, eye wash, and showers in the classroom or laboratory. Second, we need to ensure that students use appropriate personal protective equipment (PPE; e.g., sanitized indirectly vented chemical-splash goggles, chemical-resistant aprons and nonlatex gloves) during all components of laboratory activities (i.e., setup, hands-on investigation, and takedown). At a minimum, the PPE we provide for students to use must meet the ANSI/ISEA Z87.1 D.3 standard. Third, we must review and comply with all safety policies and procedures, including but not limited to appropriate chemical management, that have been established by our place of employment. Finally, and perhaps most important, we all need to adopt safety standards and better professional safety practices and enforce them inside the classroom or laboratory.

We provide safety precautions for each investigation and recommend that all teachers follow these safety precautions to provide a safer learning experience inside the classroom. The safety precautions associated with each lab investigation are based, in part, on the use of the recommended materials and instructions, legal safety standards, and better professional safety 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.

We also recommend that you encourage students to read the National Science Teacher Association's document *Safety in the Science Classroom, Laboratory, or Field Sites* before allowing them to work in the laboratory for the first time. This document is available online at *www.nsta.org/docs/SafetyInTheScienceClassroomLabAndField.pdf.* Your students and their parent(s) or guardian(s) should then sign the document to acknowledge that they understand the safety procedures that must be followed during a school science laboratory experience.

Remember that a lab includes three parts: (1) setting up the lab and preparing the materials, (2) conducting the actual investigation, and (3) the cleanup, also called the takedown. The safety procedures and PPE we recommend for each investigation apply to all three parts.

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Teacher Notes

Lab 9. Falling Objects and Air Resistance: How Does the Surface Area of a Parachute Affect the Force Due to Air Resistance as an Object Falls Toward the Ground?

Purpose

The purpose of this lab is for students to *apply* what they know about the core idea of forces and motion, part of the disciplinary core idea (DCI) of Motion and Stability: Forces and Interactions from the *NGSS,* to determine how the surface area of a parachute affects the force due to air resistance as an object falls toward the ground. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Systems and System Models and (b) Structure and Function from the *NGSS.* In addition, this lab can be used to help students understand three big ideas from AP Physics: (a) fields existing in space can be used to explain interactions, (b) the interactions of an object with other objects can be described by forces, and (c) interactions between systems can result in changes in those systems. As part of the explicit and reflective discussion, students will also learn about (a) how the culture of science, societal needs, and current events influence the work of scientists; and (b) the role of imagination and creativity in science.

Underlying Physics Concepts

Newton's second law can be written in many ways, but the most common is shown in Equation 9.1, where $\sum \mathbf{F}$ is the net force acting on an object, $\mathbf{a}$ is the acceleration of the object, and m is the mass of the object. In SI units, force is measured in newtons (N), mass in kilograms (kg), and acceleration in meters per second squared (m/s^2).

$$\textbf{(Equation 9.1)} \quad \sum \mathbf{F} = m\mathbf{a}$$

When ignoring the effect of air resistance on a falling object, we can easily solve the equation because the force of gravity is the only force acting on the object. This force will lead to an acceleration equal to −9.8 m/s^2. The equation, however, becomes more complex when we account for air resistance. When air resistance is included, we can rewrite Equation 9.1 as Equation 9.2, where $\mathbf{F}_g$ is the force of gravity and $\mathbf{F}_D$ is the force of air resistance, also referred to as the drag force, or the drag on the falling object.

$$\textbf{(Equation 9.2)} \quad \mathbf{F}_g + \mathbf{F}_D = m\mathbf{a}$$

$\mathbf{F}_g$ is easily calculated as the mass of the object times the acceleration due to gravity. The drag force, however, is a bit more complex. Equation 9.3 shows the drag force, where C_D is the coefficient of drag (related to the type of material used for the parachute) and is unitless; ρ (spelled rho and pronounced "row") is the density of air in kilograms per meter cubed (kg/m^3); **v** is velocity of the parachute in meters per second (m/s), and *A* is the surface area of the parachute in meters squared (m^2).

$$\textbf{(Equation 9.3)} \quad \mathbf{F}_D = C_D \rho \mathbf{v}^2 A/2$$

There are two important things to point to in this equation. First, and related most directly to this lab, is that the drag force on a parachute is directly proportional to the surface area of the parachute. The larger the surface area, the larger the drag force will be. This also means that if we find the value for the drag force and place it into Equation 9.2 that shows the sum of the forces acting on the falling object, then the relationship between the surface area of the parachute and the resulting acceleration is inversely proportional. As surface area increases, the net acceleration while falling will decrease.

The second important thing to point out with respect to Equation 9.3 is that the drag force is also a function of the velocity of the falling object. As the object's velocity increases, the drag force also increases and the resulting acceleration of the object decreases. When the object is at rest (i.e., when time [*t*] equals zero seconds, or when the object is released), there is no drag on the object due to the parachute. Only after the object begins to move does the drag force change the acceleration.

As the velocity increases, the drag on the parachute will continue to increase until the object reaches terminal velocity (this won't happen in this investigation, because students are not dropping from a great enough height). Terminal velocity occurs when the drag force is equal to the force of gravity. At this point, the sum of the forces equals zero, and the resulting acceleration will be zero. Furthermore, *this means that the acceleration is not constant when an object falls and we account for air resistance.* Instead, the acceleration is continuously changing until the object reaches terminal velocity, at which point the acceleration is zero.

That being said, students can find the average acceleration of their object during free fall. One way to do this is by using kinematics equations and solving for the acceleration of the object for each surface area tested. Students can do this using Equation 9.4, where **a** is acceleration, **y** is the vertical displacement, $\mathbf{v}_0$ is the initial velocity, and *t* is the time the object was falling. In SI units, displacement is measured in meters (m); velocity is measured in meters per second (m/s); and time is measured in seconds (s).

$$\textbf{(Equation 9.4)} \quad \mathbf{y} = \mathbf{v}_0 t + \tfrac{1}{2}\mathbf{a}t^2$$

If the object is released from rest, then $\mathbf{v}_0 = 0$, and the average net acceleration over the displacement, **y,** can be calculated using Equation 9.5.

$$\textbf{(Equation 9.5)} \quad \mathbf{a} = 2\mathbf{y}/t^2$$

If students are using video analysis software, they can also use the software to find the function for acceleration as a function of time. If they are familiar with calculus, they can use the mean value theorem to find the average acceleration while the object was falling toward the ground.

Timeline

The instructional time needed to complete this lab investigation is 220–280 minutes. Appendix 3 (p. 531) provides options for implementing this lab investigation over several class periods. Option A (280 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option A can also be used if you are introducing students to the video analysis programs. Option B (220 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option B, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed to implement this investigation are listed in Table 9.1. Most of the equipment can be purchased from a science supply company such as Carolina, Flinn Scientific, PASCO, Vernier, or Ward's Science. The washers and the plastic bags can be purchased from a general store, such as Wal-Mart or Target. Video analysis software can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 9.1

Materials list for Lab 9

Item	Quantity
Consumables	
Large plastic trash bags	Several per group
Tape	1 roll per group
String or fishing line	1 roll per group
Equipment and other materials	
Safety glasses or goggles	1 per student
Electronic or triple beam balance	1 per group
Washers	Several per group
Stopwatch	1 per student
Ruler	1 per student
Meterstick	1 per group
Investigation Proposal C (optional)	1 per group
Whiteboard, 2' × 3'*	1 per group
Lab Handout	1 per student
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student
Equipment for video analysis (optional)	
Video camera	1 per group
Computer or tablet with video analysis software	1 per group

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move (such as a dynamics track). A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as stopwatches, metersticks, or hanging masses). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions

Remind students to follow all normal lab safety rules. In addition, tell the students to take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Do not throw the washers or parachutes.
3. Do not stand on tables or chairs.
4. Wash hands with soap and water after completing the lab.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core idea they used during the investigation. The following are some important concepts related to the core idea of forces and motion that students need to use to determine how the surface area of a parachute affects the force due to air resistance as an object falls toward the ground:

- Gravity is an attractive force between two objects that have mass.
- Objects accelerate toward the center of Earth when in free fall because of the gravitational force between the object and Earth.
- *Displacement* is a change in position. *Velocity* is the rate of change of position over a period of time. *Acceleration* is the rate of change in velocity over a period of time.
- *Air resistance* is the result of an object moving through a layer of air and colliding with air molecules. The force of air resistance acting on a falling object is therefore dependent on the velocity and the cross-sectional surface area of the falling object.
- Force is considered a vector quantity because a force has both magnitude and direction.
- The net force acting on an object is the vector sum of the individual forces acting on it.
- The acceleration of an object interacting with other objects can be predicted by using the equation $\mathbf{a} = \sum \mathbf{F}/m$.

To help students reflect on what they know about forces and motion, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least two CCs that students need to use to determine how the surface area of a parachute affects the force due to air resistance as an object falls toward the ground: (a) Systems and System Models and (b) Structure and Function (see Appendix 2 [p. 527] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. Why is it useful to define a system and then make a model of it in science? What were the boundaries and components of the system you studied during this investigation?
2. What models did you use during the investigation? What were some of the limitations of these models?
3. The way an object is shaped or structured determines many of its properties and how it functions. Why is it useful to think about the relationship between structure and function during an investigation?
4. Why was it important to examine the structure of a parachute in order to determine its ability to slow the acceleration of a falling object? Why is an understanding of the relationship between the structure and function of parachute more useful than simply knowing which parachute works the best?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) how the culture of science, societal needs, and current events influence the work of scientists; and (b) the role of imagination and creativity in science (see Appendix 2 for a brief description of these two concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. People view some types of research as being more important than other types of research because of cultural values and current events. Can you come up with some examples of how cultural values and current events have influenced the work of scientists?
2. Scientists share a set of values, norms, and commitments that shape what counts as knowing, how to represent or communicate information, and how to interact with other scientists. Can you work with your group to come up with a rule that you can use to decide if something is science or not science? Be ready to share in a few minutes.
3. Some people think that there is no room for imagination or creativity in science. What do you think?
4. Can you work with your group to come up with different ways that you needed to use your imagination or be creative during this investigation? Be ready to share in a few minutes.

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of research projects that were influenced by cultural values or current events and ask students to think about what was going on at the time and why that research was viewed as being important for the greater good.

You can also show students an image of the following quote by E. O. Wilson from *Letters to a Young Scientist* (2013) and ask them what they think he meant by it:

> The ideal scientist thinks like a poet and only later works like a bookkeeper. Keep in mind that innovators in both literature and science are basically dreamers and storytellers. In the early stages of the creation of both literature and science, everything in the mind is a story. There is an imagined ending, and usually an imagined beginning, and a selection of bits and pieces that might fit in between. In works of literature and science alike, any part can be changed, causing a ripple among the other parts, some of which are discarded and new ones added. (p. 74)

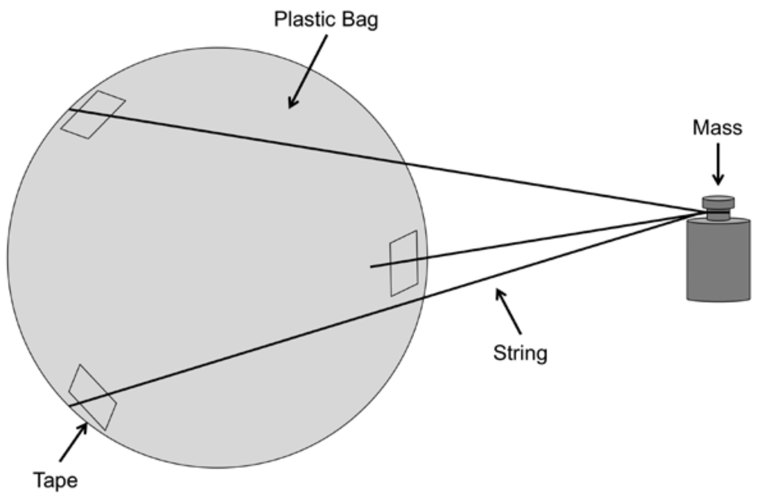
Be sure to remind your students that, to be proficient in science, it is important that they understand what counts as scientific knowledge and how that knowledge develops over time.

Hints for Implementing the Lab

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their procedure by having them fill out an investigation proposal. These proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. For this lab we suggest using Investigation Proposal C.
- Allow the students to become familiar with the equipment and materials as part of the tool talk before they begin to design their investigation. Giving them 5–10 minutes to examine the equipment and materials will let students see what they can and cannot do with them.
- If too much mass is added to the parachute, this may result in the parachute ripping or breaking. The limit on the mass to be added to the parachute is dependent on the type of plastic. The thicker the plastic, the more mass it can support. In general, a mass of 50 g–250 g will be sufficient.
- Students will sometimes create parachutes that are rectangles to make it easier to calculate the surface area. As a result, they may create parachutes that are too long and thin to work well. Figure 9.1 (p. 204) shows an example of how students might create their parachutes, but there are other ways that they can design them.
- The higher up the students can be when they drop their parachutes, the more pronounced the effect. We suggest having students drop the parachutes from the top of the bleachers at the football field or from a balcony two stories high.

FIGURE 9.1

A possible design of a parachute



- Encourage students to derive an expression for the acceleration as a function of time for an object falling under the influence of drag forces as their answer to the guiding question.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

If students use video analysis

- We suggest allowing students to familiarize themselves with the video analysis software before they finalize the procedure for the investigation, especially if they have not used such software previously. This gives students an opportunity to learn how to work with the software and to improve the quality of the video they take.
- Remind students to hold the video camera as still as possible. Any movement of the camera will introduce error into their analysis. If using actual camcorders, we recommend using a tripod to hold the camera steady. If students are using a

camera on a cell phone or tablet, we recommend using a table to help steady the camera.

- Remind students to place a meterstick in the same field of view as the motion they are capturing with the video camera. Also, the meterstick should be approximately the same distance from the camera as the motion. Most video analysis software requires the user to define a scale in the video (this allows the software to establish distances and, subsequently, other variables dependent on distance and displacement).

Connections to Standards

Table 9.2 (p. 206) highlights how the investigation can be used to address specific performance expectations from the *NGSS;* learning objectives from AP Physics 1; learning objectives from AP Physics C: Mechanics, *Common Core State Standards,* in English language arts (*CCSS ELA*); and *Common Core State Standards,* Mathematics (*CCSS Mathematics*).

TABLE 9.2

Lab 9 alignment with standards

***NGSS* performance expectation**	• HS-PS2-1: Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.
AP Physics 1 learning objectives	• 3.A.1.2: The student is able to design an experimental investigation of the motion of an object. • 3.A.1.3: The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. • 3.B.1.2: The student is able to design a plan to collect and analyze data for motion (static, constant, or accelerating) from force measurements and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces.
AP Physics C: Mechanics learning objectives	• I.B.2.a: Students should understand the relation between the force that acts on an object and the resulting change in the object's velocity so they can: • I.B.2.a(1): Calculate, for an object moving in one dimension, the velocity change that results when a constant force **F** acts over a specified time interval. • I.B.2.a(2): Calculate, for an object moving in one dimension, the velocity change that results when a force **F**(*t*) acts over a specified time interval. • I.B.2.b: Students should understand how Newton's second law, applies to an object subject to forces such as gravity, the pull of strings, or contact forces. • I.B.2.c: Students should be able to analyze situations in which an object moves with specified acceleration under the influence of one or more forces so they can determine the magnitude and direction of the net force, or of one of the forces that makes up the net force, such as motion up or down with constant acceleration. • I.B.2.e: Students should understand the effect of drag forces on the motion of an object, so they can: • I.B.2.e(1): Find the terminal velocity of an object moving vertically under the influence of a retarding force dependent on velocity. • I.B.2.e(2): Describe qualitatively, with the aid of graphs, the acceleration, velocity, and displacement of such a particle when it is released from rest or is projected vertically with specified initial velocity. • I.B.2.e(3): Use Newton's second law to write a differential equation for the velocity of the object as a function of time. • I.B.2.e(4): Use the method of separation of variables to derive the equation for the velocity as a function of time from the differential equation that follows from Newton's second law. • I.B.2.e(5): Derive an expression for the acceleration as a function of time for an object falling under the influence of drag forces.

Literacy connections (*CCSS ELA*)	• *Reading:* Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing:* Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas
Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices:* Make sense of problems and persevere in solving them, reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, model with mathematics, use appropriate tools strategically, attend to precision, look for and make use of structure, look for and express regularity in repeated reasoning • *Number and quantity:* Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra:* Interpret the structure of expressions, create equations that describe numbers or relationships, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically • *Functions:* Understand the concept of a function and use function notation, interpret functions that arise in applications in terms of the context, analyze functions using different representations, build a function that models a relationship between two quantities, construct and compare linear and exponential models and solve problems, interpret expressions for functions in terms of the situation they model • *Statistics and probability:* Summarize, represent, and interpret data on two categorical and quantitative variables; interpret linear models; understand and evaluate random processes underlying statistical experiments; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Reference

Wilson, E. O. 2013. *Letters to a young scientist.* New York: Liveright Publishing.

Lab Handout

Lab 9. Falling Objects and Air Resistance: How Does the Surface Area of a Parachute Affect the Force Due to Air Resistance as an Object Falls Toward the Ground?

Introduction

When we solve motion problems in physics, we often neglect to take into account the effects of air resistance because, at slow speeds, they are relatively small compared with the force of gravity. Other times, we ignore air resistance when we perform calculations in order to simplify the problem. However, some devices like kites and parachutes are designed to use air resistance in order to function. In these cases, scientists need to account for the effect of air resistance on falling objects.

Besides being used for recreational purposes such as skydiving, parachutes play an important role in the humanitarian efforts of many governments. One of the first uses of parachutes to aid humanitarian efforts was the Berlin Airlift of 1948–1949 (*www.history.com/this-day-in-history/berlin-airlift-begins*). As tensions rose at the onset of the Cold War, the Soviet Union prevented any people or goods from entering West Berlin in Germany. In response, the United States and United Kingdom organized efforts to airdrop food, supplies, and coal (for power) into West Berlin. By the end of the Soviet blockade in 1949, over 200,000 flights had been made into and over Berlin.

FIGURE L9.1

An airdrop of food and medical supplies after a major earthquake in Haiti

The airdrop remains one of the more effective tools for bringing food and necessary supplies, such as medicine, to people that need it. Figure L9.1, for example, is a picture of the airdrop that took place in Haiti after the 2010 earthquake that nearly destroyed the city of Port-au-Prince.

Air resistance affects the net force acting on a falling object, although in some conditions the effect is negligible and/or not observable. Newton's second law states that the acceleration produced by a net force on an object is directly proportional to the magnitude of the net force, is in the same direction as the net force, and is inversely proportional to the mass of an object; or, in mathematical terms, acceleration equals net force divided by mass.

The acceleration of a falling object without air resistance is −9.8 m/s^2 because the net force acting on the falling object is equal to the force of gravity. However, when air resistance is present, then the net force on the object changes, because the force of air resistance counters the force of gravity.

An engineer needs to consider several different issues and work through a multistep design process in order to create a new parachute. The first step in the design process is to determine the performance specifications of the new parachute. This step requires the engineer to think about the minimum and maximum mass of any object that will be attached to the parachute and the maximum terminal velocity that the object will reach as it falls to the ground. Terminal velocity is the highest velocity attainable by an object as it falls through the air. Terminal velocity occurs when the drag force acting on the falling object is equal to the force of gravity. At this point, the sum of the forces acting on the object equals zero, and the resulting acceleration will be zero. A safe landing velocity for an object is usually between 2 and 5 m/s. The second step in the design process is to build a parachute with a specific surface area that will meet these important performance specifications. It is therefore important for engineers to understand how the surface area of a parachute affects the force of air resistance that acts on an object as it falls to the ground.

Your Task

Use what you know about forces and motion, structure and function, and models to design and carry out an investigation to determine how parachute surface area affects the force due to air resistance.

The guiding question of this investigation is, ***How does the surface area of a parachute affect the force due to air resistance as an object falls toward the ground?***

Materials

You may use any of the following materials during your investigation:

Consumables
- Large trash bags
- Tape
- String or fishing line

Equipment
- Safety glasses or goggles (required)
- Electronic or triple beam balance
- Washers
- Stopwatch
- Ruler
- Meterstick

If you have access to the following equipment, you may also consider using a video camera and a computer or tablet with video analysis software.

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety goggles or glasses during lab setup, hands-on activity, and takedown.
2. Do not throw the washers or the parachutes.
3. Do not stand on tables or chairs.
4. Wash hands with soap and water after completing the lab.

Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

To answer the guiding question, you will need to design and carry out an experiment. To accomplish this task, you must determine what type of data you need to collect, how you will collect it, and how you will analyze it.

To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the system you are studying?
- How do the components of the system interact with each other?
- How might the structure of a parachute relate to its function?
- How will you determine the surface area of a parachute?
- How will you measure the force of air resistance?
- What will be the independent variable and the dependent variable for your experiment?

To determine *how you will collect the data,* think about the following questions:

- What conditions need to be satisfied to establish a cause-and-effect relationship?
- What measurement scale or scales should you use to collect data?
- What equipment will you need to make the measurements?
- What other variables will you need to control during your experiment?
- Do you need to include a control group?
- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- What type of calculations will you need to make?
- What types of models can you use to help you analyze the motion of a parachute?
- How could you use mathematics to describe a relationship between variables?
- What types of patterns might you look for as you analyze your data?
- Are there any proportional relationships that you can identify?
- What type of table or graph could you create to help make sense of your data?

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

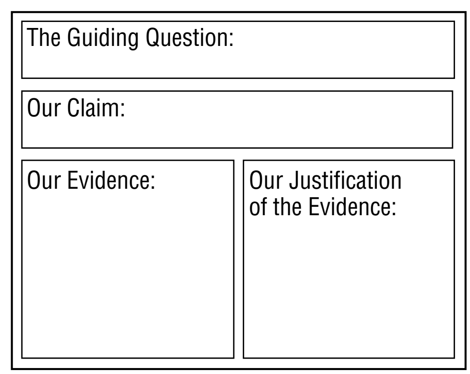
- how the culture of science, societal needs, and current events influence the work of scientists; and
- the role of imagination and creativity in science.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your initial argument needs to include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the justification of the evidence is why your group thinks the evidence matters. The *justification* of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L9.2.

FIGURE L9.2

Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an *investigation report* that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Checkout Questions

Lab 9. Falling Objects and Air Resistance: How Does the Surface Area of a Parachute Affect the Force Due to Air Resistance as an Object Falls Toward the Ground?

1. Is there a maximum force due to air resistance that can act on a parachute?

   a. Yes
   b. No

   How do you know?

   What does your answer suggest about the effect of increasing the size of the parachute?

2. The equation for the force of air resistance (more formally, the drag) on a parachute is $\mathbf{F}_D = C_D \rho \mathbf{v}^2 A/2$. In this equation, $\mathbf{F}_D$ is the drag force and $\mathbf{v}$ is the current velocity of the falling parachute and mass system. Is the drag force constant as a function of time?

   a. Yes
   b. No

   Justify your answer using the equation provided and/or data from your investigation.

3. Scientists share a set of values, norms, and commitments that shape what counts as knowing, how to represent or communicate information, and how to interact with other scientists.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about air resistance and parachutes.

4. Scientists must use their imagination and creativity to figure out new ways to test ideas and collect or analyze data.

   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using an example from your investigation about air resistance and parachutes.

5. Why is it useful to identify a system under study and then make a model of it during an investigation? In your answer, be sure to include examples from at least two different investigations.

6. Why is it important to think about the relationship between structure and function when trying to develop an explanation for a natural phenomenon? In your answer, be sure to include examples from at least two different investigations.

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

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