



The Wonder of Seeds: Investigations in Germination & Growth



Teacher's Guide Overview

Premise: Most students are familiar with seeds and plants. However, compared to even a generation ago, fewer students today have grown a plant or regularly engage in outdoor activities where they might learn firsthand about the “climbing” of kudzu vines over time or how the prickly seeds of burdock can hitch a ride back home on socks. Some students may not recognize that plants and seeds are living organisms. Understanding that an individual seed contains one dormant embryo of a young plant, and that plants are actively growing, living organisms are basic, crucial concepts in biology that both show similarities between plants and other organisms and help describe how life cycles proceed within the plant kingdom. Seeing the influence of environmental conditions on germination and plant growth is also a direct way to learn that plants, like other organisms, succeed better in some environments than others. Such knowledge is foundational to understanding that the future of a changing climate has consequences for wild ecosystems and agricultural food production alike.

How The Wonder of Seeds Works: This module consists of a lab inquiry embedded in classroom and online discussions. The lab may be used as a guided or open-ended inquiry and is flexible enough that either type (or both) can be used based on student abilities, course level, and time available. Unlike many labs, the inquiry is designed to produce results that students do not necessarily expect beforehand. By “rocking students’ boats,” the lab aims to capture the importance of the unknown in science and to demonstrate how unknowns lead to new models, hypotheses, and experiments. Worksheets can help students organize their ideas and reflect on their thinking, either on the computer or in handwriting.

Beyond lab activities, three other activities are essential to fully benefit from this module:

- **ScienceTalk:** an authentic classroom *dialogue* before and/or while experiencing lab activities,
- **ResearchBlogs:** regular *online contact* between students and scientist mentors, and
- **Storyboard Discussion:** an extended post-lab discussion in which students *share and reconcile data* within and across teams.

We have found that a teacher’s commitment to dialogue and a focus on students’ ideas and reasoning emphasizing the process of science, rather than correct answers, are important to building an open culture for science learning. Explanations using everyday vocabulary are valued over use of scientific vocabulary in the absence of explanations. Additional descriptions of teaching and learning strategies can be found on the “Roadmap Through a Science Project” section of the [PlantingScience](#) website.

Grade levels: Middle school and high school biology, AP biology, environmental science, AP environmental science, horticulture, botany, and other life science electives.

Class Time: A three-week investigation will allow enough time to complete either the guided or open inquiry lab.

Computer Access: Optimally, daily while designing an experiment and every other class session thereafter; minimally, at least 3 times over the course of the full investigation period. Team blogs require logins.

Crosscutting Concepts & Practices from the Next Generation Science Standards:

CONCEPTS	SCIENTIFIC PRACTICES
<ul style="list-style-type: none"> • Matter is transported into, out of, and within systems (5-LS1-1) • A system can be described in terms of its components and their interactions (5-LS2-1) • Phenomena may have more than one cause, and some cause and effect relationships can only be described using probability (MS-LS1-4, MS-LS1-5) • Cause and effect relationships may be used to predict phenomena in natural or designed systems (MS-LS2-1) • The transfer of energy can be tracked as energy flows through a natural system (MS-LS2-3) • Science assumes that objects and events in natural systems occur in consistent patterns that are understandable through measurement and observation (MS-LS2-3) • Models can be used to simulate systems and interactions – including energy, matter, and information flows – within and between systems at different scales (HS-LS1-4) • Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system (HS-LS1-5) 	<ul style="list-style-type: none"> • Support an argument with evidence, data, or a model (5-LS1-1) • Develop a model to describe phenomena (5-LS2-1) • Science explanations describe the mechanisms for natural events (5-LS2-1) • Construct a scientific explanation based on valid and reliable evidence (MS-LS1-5, MS-LS1-6) • Use an oral and written argument supported by empirical evidence and scientific explanation to support or refute an explanation or a model for a phenomenon or a solution to a problem (MS-LS1-4) • Science knowledge is based upon logical connections between evidence and explanations (MS-LS1-6) • Develop a model to describe phenomena (MS-LS2-3) • Analyze and interpret data to provide evidence for phenomena (MS-LS2-1) • Use a model based on evidence to illustrate the relationships between systems or between components of a system (HS-LS1-4, HS-LS1-5)

Disciplinary Core Ideas from the Next Generation Science Standards:

GERMINATION	PLANT GROWTH
<ul style="list-style-type: none"> • Growth and Development of Organisms (MS-LS1.B) <ul style="list-style-type: none"> ○ Plants reproduce in a variety of ways, sometimes depending on animal behavior and specialized features for reproduction (MS-LS1-4) • Energy in chemical processes and everyday life (MS-PS3.D) <ul style="list-style-type: none"> ○ Cellular respiration in plants and animals involve chemical reactions with oxygen that release stored energy. In these processes, complex molecules containing carbon react with oxygen to produce carbon dioxide and other materials (secondary to MS-LS1-7) • Ecosystem Dynamics Functioning and Resilience (MS-LS2.C) <ul style="list-style-type: none"> ○ The atoms that make up the organisms in an ecosystem are cycled between the living and nonliving parts of the ecosystem (MS-LS2-3) 	<ul style="list-style-type: none"> • Organization for Matter and Energy Flow in Organisms (5-LS1.C) <ul style="list-style-type: none"> ○ Plants acquire their material for growth chiefly from air and water (5-LS1-1) • Growth and Development of Organisms (MS-LS1.B) <ul style="list-style-type: none"> ○ Genetic factors as well as local conditions affect the growth of the adult plant (MS-LS1-5) • Energy in Chemical Processes and Everyday Life (MS-PS3.D) <ul style="list-style-type: none"> ○ The chemical reaction by which plants produce complex food molecules requires an energy input to occur. (secondary to MS-LS1-6) • Organization for Matter and Energy Flow in Organisms (HS-LS1.C) <ul style="list-style-type: none"> ○ The process of photosynthesis converts light energy to stored chemical energy by converting carbon dioxide plus water into sugars plus released oxygen (HS-LS1-5)
LINKING GERMINATION & PLANT GROWTH	
<ul style="list-style-type: none"> • Interdependent relationships in ecosystems (5-LS2.A) <ul style="list-style-type: none"> ○ The food of almost any kind of animal can be traced back to plants. Organisms can survive only in environments in which their particular needs are met (5-LS2-1) • Cycles of Matter and Energy (5-LS2.B) <ul style="list-style-type: none"> ○ Organisms obtain gases and water from the environment, and release waste matter (gas, liquid, or solid) back into the environment (5-LS2-1) • Organization for Matter and Energy Flow in Organisms (MS-LS1.C) <ul style="list-style-type: none"> ○ Plants use the energy from light to make sugars (food) from carbon dioxide from the atmosphere and water through the process of photosynthesis, which also releases oxygen. These sugars can be used immediately or stored for growth or later use (MS-LS1-6) ○ Within individual organisms, food moves through a series of chemical reactions in which it is broken down and rearranged to form new molecules, to support growth, or to release energy (MS-LS1-7) • Interdependent relationships in Ecosystems (MS-LS2.A) <ul style="list-style-type: none"> ○ Organisms are dependent on their environmental interactions both with other living things and with nonliving factors (MS-LS2-1) ○ Growth of organisms is limited by access to resources (MS-LS2-1) • Growth and Development of Organisms (HS-LS1.B) <ul style="list-style-type: none"> ○ The organism begins as a single cell that divides successfully to produce many cells. Cellular division and differentiation produce and maintain a complex organism, composed of systems of tissues and organs that work together to meet the needs of the whole organism (HS-LS1-4) 	



The Wonder of Seeds: Investigations in Germination & Growth



Teacher's Guide
Planner

Suggested Schedule of Activities: The core of **The Wonder of Seeds** consists of an inquiry on germination or plant growth in which student teams ask a research question and carry out an experiment to help answer it. The inquiry may be guided or open, depending on student abilities and performance expectations. The module can be preceded by or extended with another inquiry, such as **Corn Competition** or **Power of Sunlight**, or continue after the experiment by tracking the remainder of the plants' life cycle.

Sample Topic	Pre-Lab Science Talk	Blogging	Lab Activity	Blogging	Post-Lab Storyboard Discussion	Blogging
<i>Exploring the Impact of Environment on Germination</i>	Are seeds alive?	With Scientists	Exploring rates of germination	With Scientists	How do plants grow during germination?	With Scientists
<i>Exploring the Impact of Environment on Plant Growth</i>	What is happening during growth?	& Peers	Exploring seedling biomass	& Peers	How does the environment influence plant growth?	& Peers

Suggested Assessment Schema: The module is designed so that students can be assessed *continuously* for changes in understanding. The pre-lab ScienceTalk, teacher interaction with teams during lab activities, lab journals and worksheets, and blogging online all serve as embedded formative assessment tools. The post-lab class Storyboard Discussion, a final individual reflection, and the post-experience survey serve as summative assessment tools. If desired, summative assessment in an exam format could involve written responses to questions such as:

- What is dormancy?
- What resources are necessary for a plant to grow?
- Is it possible for a plant to have too much of a resource?
- Describe the life cycle of a flowering plant.

Examples of possible assessment rubrics are available on the **PlantingScience** website (https://plantingscience.org/resources/31/download/PS_TeachersHandbook_2013_2.pdf).

Additional Resources: *Germination and Growth Resources* contains a bibliography of online videos, websites, books, and articles, organized by media type. Items may relate directly to biological

processes, to classroom tools and techniques for teaching about the process, or to research on effective teaching and student misconceptions.

Coordinating with the Scientist Mentor: Please let your scientist mentor(s) know...

- your expected start and end dates for interacting with students online,
- how frequently your students meet,
- how often students will have computer access, and
- whether you plan to carry out a guided or open inquiry (or both).

Time Needed: At least three weeks will be needed to complete the growth inquiry; questions focusing only on germination may take less time. One or two additional weeks will allow deeper exploration of the plant life cycle or implementation of the alternative schemes described in more detail in the **Inquiry Lab** section on p. 10.



Students should work in teams of 2-4, and individual team members are encouraged to post online. The image at left indicates opportunities for team **Research Blogging** in the schedule on the next page. Teams may blog from school or from home.

Suggested plan: A calendar-style outline for carrying out a single, open inquiry is provided on the next page. The plan that is shown assumes that the class meets daily for 45-60 minute periods. Classes on a block schedule can follow a plan similar to that for the daily schedule, with the initial ScienceTalk, scientist prompt, and brainstorming taking place on Monday of Week 1. Students can then come in to the lab for about 20 min on Thursday of Week 1 to “plant” the seeds after preparations on Wednesday. During Weeks 2 and 3, students may be required to monitor on non-class days, or on class days only, depending on teacher preference. Wednesday of Week 3 provides good timing for final data collection, team data analysis, and team storyboard preparation for discussion on Friday. Alternatively, the inquiry could be extended into Week 4 to avoid having students come to the lab on days when they do not have class.

Sample Outline for an Open Inquiry:

	Mon	Tue	Wed	Thu	Fri
Week 1	<p>Scientist Prompt: <i>What have you been doing with plants in your class? Are seeds alive? What do plants need to grow?</i></p> <p>Blog: Register, set up team website, & make first post to scientist.</p> 	<p>ScienceTalk: What is happening during growth? (+ video)</p> <p>Scientist Prompt: <i>What do you think it means to grow? What do you think are good measures of growth?</i></p>	<p>Teams brainstorm a research question & write up a research plan.</p> <p>Blog: Reflect on Science Talk & brainstorming ideas.</p> 	<p>Blog: Read scientists' notes & follow up with the research plan.</p>  <p>Teams may need to modify the research plan based on feedback; prepare experimental materials.</p> <p>20 min – Weigh, sterilize, soak seeds.</p>	<p>20 min – “Plant” seeds.</p>
Week 2	<p>Blog: Upload photos & data from on-going experiment; contact scientist for questions or troubleshooting.</p> <p>Observe seed(ling)s & collect data.</p> 	<p>Observe seed(ling)s & collect data.</p>	<p>Blog: Upload photos & data; contact scientist for questions or troubleshooting.</p> <p>Observe seed(ling)s & collect data.</p> 	<p>Observe seed(ling)s & collect data.</p>	<p>Blog: Upload photos & data; contact scientist for questions or troubleshooting.</p> <p>Observe seed(ling)s & collect data.</p> 
Week 3	<p>Blog: Upload photos & data; contact scientist for questions or troubleshooting.</p>  <p>Observe seed(ling)s & collect data.</p>	<p>Observe seed(ling)s & collect data.</p>	<p>Blog: Upload photos & data; contact scientist for questions or troubleshooting.</p>  <p>Observe seed(ling)s & collect data.</p>	<p>Last day of data collection. Analyze data, then prepare storyboard.</p>	<p>Blog: Wrap up with research conclusions & ideas for new experiments (summative).</p> <p>Storyboard Discussion: Share & reconcile understandings of growth & germination (summative).</p> 

How do diversity and the environment influence seed germination and plant growth?

*What does it really mean “to grow”? Is it different from germination?
What are the characteristics of each?*



OPEN OR GUIDED INQUIRY ON GERMINATION & PLANT GROWTH

GOALS & TIMELINE (see **Planner** for sample schedule options)

Goals:

- Develop models for understanding germination or growth
- Understand the scientific research process
- Design and carry out an experiment
- Observe seedling growth and development
- Consider and reconcile data from multiple sources

Sample sequence:

- *Days 1-2:* Create teams; set up team ResearchBlog and make first entry; ScienceTalk
- *Day 3:* Develop research question* and experimental design; ResearchBlog
- *Day 4:* Refine experimental design; weigh, sterilize, & soak seeds; ResearchBlog
- *Day 5:* “Plant” seeds
- *Days 6-14:* Collect data regularly; ResearchBlog
- *Days 14-15:* Analyze data; develop storyboards; Storyboard Discussion; final ResearchBlog

*(Open inquiry)

Student Handouts:

The Wonder of Seeds Student’s Guide
Brainstorming Page worksheet
About our Research Question worksheet*
Experimental Design worksheet
Making Sense of the Data worksheet
[Student Roadmap](#) (optional)

Background: Students will generate ideas about seed germination and about how to tell if something is growing. Students’ ideas about these biological processes can be taken from their own experiences, discussed in everyday language, and translated into biologically meaningful conceptual models. Students may develop a specific research question, design an experiment, and draw conclusions from the data to refine their working model of germination or growth. The teachers’ role is to (a) help students use sound reasoning and evidence to develop an experimental design that clearly addresses a research question and will allow students to build explanations based on the results, while also (b) facilitating connections to deeper concepts and scientific practices.

Activity 1: SCIENTETALK (Allow 20 min to half a class period; follow up with ResearchBlog)

Juicy Questions:

- Are seeds alive?
- What causes germination?
- Is it possible to drown a seed?
- Do seeds need soil to germinate?
- **Where does an acorn get all its weight from to become an oak tree?**
- **Does growth always mean gaining weight?**
- **What does a plant need to grow?**
- **What are good measures of growth?**
- **Can plants grow in darkness/at night?**

The ScienceTalk and subsequent lab inquiry can emphasize either **germination** or **plant growth** by selecting Juicy Questions accordingly.

Video Resources:

<http://www.ted.com/index.php/talks/richard-preston-on-the-giant-trees.html> (First 4.5 min).

Richard Preston on the giant trees presents the problem of biomass accumulation in an ecological context, and uses a good visual to ask the seed-to-tree question.

http://www.teachersdomain.org/asset/tdc02_vid_photosynth/ (2.5 min).

What do plants use for nourishment? Depicts von Helmont’s experiment demonstrating that a willow’s weight does not come from soil and introduces photosynthesis.

Key Features of and Suggestions for the ScienceTalk:

The key features of a ScienceTalk, beyond the Juicy Questions, are shown below in *red*. Many suggestions for implementing these features are shown, but feel free to develop your own approach suited to the class.

1. *Engage and explore prior knowledge:*

- Introduce seed germination and/or seedling growth
 - Show a video or link from **Growth and Germination Resources** to open a conversation.
 - You may focus more strongly on **germination** or **plant growth** if students will explore only one of these for the inquiry.
- Connect the topic to everyday life and its relevance to society
 - Brainstorm with students about ways that seed biology might be important to society.
 - Start with a personal story, e.g., “I was in the grocery store buying beans for my chili....”
 - Use a hypothetical scenario for context, e.g., the class is a sprout farming business and needs a plan to maximize seedling growth.
- Probe for prior knowledge
 - Ask students what they know, think they know, and want to know (KWL) about “sprouting seeds.”
 - A good starting question is “Where do seeds come from?”
 - Continuing the personal story can also probe for prior knowledge.
 - For example, “I wondered what we are eating when we eat beans and why I have to soak my chili beans overnight to eat them. What do you think?”
 - More sophisticated observations may be called for in upper-level or advanced classes. Probe student answers for reasoning; e.g., does soaking seeds just hydrate them, or does something else happen?

- Explore seed diversity, structure, and function
 - Place seeds from several different plant species on the table for students to compare, contrast, and ask questions about. Brainstorm about what differences in seed morphology might mean for germination.
 - Soak lima beans overnight. Students can dissect them to identify the parts of a seed.
 - Play the “Branching Out” segment of *The Private Life of Plants*, a 6-part video series.

2. *Introduce scientific inquiry concepts:*

- Facilitate a discussion of what it means to **germinate** or **grow** to help students begin developing *models* for these processes.
 - This is a prelude to working out how to recognize germination or growth during experiments.
 - The discussion will lead to questions about good *measures* of germination or growth.
 - Write students’ ideas on the board or have them take notes for when they design their experiments.
- Facilitate a discussion on factors that create favorable *conditions* for germination or growth.
 - Brainstorm with students as to why many seedlings and much new growth are seen in springtime.
 - Environmental factors that can play roles in germination include light intensity/quality, soil type, length of imbibing seeds (soaking in water), or composition of soaking solution.
- Discuss the inquiry process in the context of designing experiments, focusing on controls and test variables.
- Introduce the essential components of research.
 - *Data skills* include careful observing, note taking, data recording, and summarizing data.
 - *Social skills* include teamwork, sharing and building on ideas, and explaining results with and to others.
 - If desired, nudge students toward inquiries that use experiments that require similar measurements. Team-to-team consistency will allow easy comparison among teams.

Activity 2: INQUIRY LAB (Allow at least half of two class periods for experimental design, then 10-15 min per class.)

Purpose: The purpose of this lab is (a) to provide students with experience in developing and following through with their own research question* and experiment and (b) to develop conceptual connections among environmental or biological factors, seed germination, and/or plant growth.

What to Expect: Students must provide scientific and everyday rationales for their research question*, or demonstrate an understanding of a research question the teacher assigns♦. Some students have difficulty aligning their research predictions with the research question or experimental design. Anticipate that some students will not have a frame of reference for the features of a plant's environment. Most students will see this as a one-experiment inquiry. We encourage teachers to allow students some latitude to explore various questions* and to envision multiple approaches/experiments for testing a question before committing to a line of research. This broader approach better reflects how scientific research is actually conducted.

Optional Elaborations: If time permits, encourage students to think beyond the single experiment. For example, students might carry out an inquiry, then monitor plants for about 10 min during each class period through the remainder of the growth cycle. Wisconsin Fast Plants are particularly well suited to this, as they can complete a full life cycle in about 40 days. Students may also carry out multiple lab inquiries if more than three weeks are available for the module.

Several options for students to carry out multiple inquiries include:

- Once your students have completed a **germination** inquiry, use the resulting seedlings in a **plant growth** inquiry.
- The first experiment could be a *guided* inquiry, and the second could be an *open* inquiry.
- Integrate the above two options, allowing a week or two of *guided* inquiry focusing on **germination** followed by two or three weeks of *open* inquiry focusing on **plant growth**.
- Students could design a second experiment using knowledge gained or questions arising during the first.
- Environment-related questions could be addressed in the first inquiry, and diversity-related questions could be addressed in the second.
- **The Wonder of Seeds** can be integrated with **The Power of Sunlight**, allowing students to investigate respiration of seeds and seedlings or photosynthesis of seedlings. See **The Power of Sunlight Teacher's Packet** for information on this option.

*(Open inquiry) ♦(Guided inquiry)

Inquiry Types & Sample Research Topics

Mold the Inquiry to Fit Your Class:

This inquiry can be a launching point for experiments taking many directions at many different grade levels. For lower-level students, you may wish to limit the inquiry topic to either **germination** or **plant growth**, not both. For an open inquiry, guiding students from expansive “why” questions to testable “how” questions is critical. The **Student Roadmap through an Investigation** provides help for students developing their own research questions. Once teams have chosen their research questions, you may have the class gather and hear each other's choices. Have each team justify their question with evidence whenever possible. This will prepare them for the later Storyboard Discussion on their experimental findings and models for seed germination or seedling growth.

How Much Guidance Should a Guided Inquiry Provide?

Due partly to an increasing disconnect from nature in the U.S. population, many students struggle with grounding germination and growth questions in a biologically meaningful context. You may therefore wish to provide more structure by using a *guided inquiry*. You might have all teams design their own experiment, but assign the entire class a single research question or assign related questions to different teams. You could assign a general research area, within which teams develop their own, more specific research questions. Examples of appropriate questions and research areas are listed below, color-coded by biological process.

Lower-Level Students:

Research questions (and related measurements):

- **How long does it take for seeds to germinate?** (days to germination; students must define an appropriate benchmark for germination)
- **Do different seed species germinate at the same rates?** (days to germination)
- **Are the germination rates advertised on seed packets accurate?** (days to germination)
- What is the effect of seed depth in potting soil? (**days to germination or percent germination**; **days to shoot emergence or percent emergence**)
- **How fast do seedlings of a particular species grow?** (seedling length over time)

Research areas:

- **Germination success or growth rate** under different environmental conditions with **one** test variable.
- **Rate and volume of seeds' water absorption**, based on species or environmental conditions.
- Effects of biological variation among the seeds in a given species on **germination and growth**.
- **Whether changes to the seed coat influence germination.**
- **Whether changes to the cotyledons influence growth.**

Upper-Level Students:

Research questions:

- **Does fresh/dry mass change as seeds germinate?** (Measure at multiple time points.)
- **How does seedling dry mass relate to length over time?** (Measure at multiple time points.)
- **Does the anatomy of dark-grown seedlings differ from that of light-grown seedlings?** (Encourage quantitative measurements as well.)
- Does sowing seeds at different densities affect their **germination** or **growth**?
- Does **germination** or **growth** of transgenic and organic seeds differ?
- Does **germination** or **growth** differ for seeds from invasive and native species, and does it depend on whether the species are grown separately or together?

Research areas:

- **Tropisms: how do seedlings respond to a changing orientation with respect to gravity, light, or touch?**
- *Environmental science:* how do pollutants affect **germination** and **growth**?
- *Ecology:* What seeds are present in the seed bank in a local field or forest? Compare their **germination** and **growth** patterns.
- *Physiology:* Links to **The Power of Sunlight**; When do respiration and photosynthesis begin?

Plant Materials	Other Materials (per team)
<p>Each team will need seeds sufficient for at least two treatment groups. However, few plants species have 100% germination success, so students should plant more seeds than necessary. Within each treatment:</p> <ul style="list-style-type: none"> Planting at least five seeds should allow students to calculate an average for measurements such as mass or height. Planting at least ten seeds will yield one calculation for percent germination; to calculate <i>average</i> percent germination, at least three such replicates are needed. <p>Selecting plants: Some seeds show improved germination rates if first <i>stratified</i>, placed under damp, cold conditions for weeks before planting. Some seeds may germinate during this phase. Seeds requiring stratification should be used only for plant growth experiments after advance stratification. Seed packets usually note when this step is helpful.</p>	<ul style="list-style-type: none"> Petri dishes, plastic bags, or empty bottles for germination experiments (see the <i>Wonder of Seeds Student Guide</i>) Paper towels Sharpie marker Water Pots or cups for plant growth experiments Light source (40W or higher) Ruler String (Optional) Magnifying lens (Optional) Digital camera Means to monitor or control environmental conditions based on the research question: <ul style="list-style-type: none"> Thermometer and heater/cooler Colored lights or light filters Light timers Table salt Fertilizer Acid or base solution and pH meter or strips
Experimental Design	
<p>Suggested Requirements: Regardless of whether the inquiry is guided or open, students should design their own experiments to address their research question. Encourage students to plan to record both quantitative and qualitative data. Drawings or photos of seeds and seedlings at different stages are useful for monitoring unexpected changes, and including at least one set of measurements will give students experience with summarizing data.</p> <p>Available Methods and Tools: You might help students think about their options during this phase by putting out the tools and instruments that they can have access to in conducting their experiments. If students have ideas that require other tools or instruments and they can bring them to class or you can acquire them easily, consider expanding the options on a team-by-team basis.</p> <p>Refining the Experimental Design: After teams have drafted their research plans, they should post them to the team blog for feedback from their scientist mentor. Students often have constructive ideas on how to improve each other’s work at this point, so you could also ask teams to read each other’s blogs and provide feedback online. Remind students to focus on constructive criticism aimed toward improving the experiments. Teams can then modify their experiments based on feedback.</p> <p><i>Alternatively,</i> reviews can be carried out in the classroom, with teams presenting their experimental designs to the class or circulating amongst each other to hear each other’s plans and give feedback. Discuss comparing data across teams. Will the types of measurements and units planned create comparable data? Does it matter? If so, how can students change their experiments to allow easy comparisons within the class or with other classes doing the inquiry?</p>	

Logistics	Technical Notes
<p>Detailed procedures for carrying out experiments and considerations of lab safety are described in <i>The Wonder of Seeds Student Guide</i>.</p> <p>Students should work in teams of 2-4. Each team will design and carry out experiments separately from the others to answer their own or a selected research question, based on the type of inquiry you choose.</p> <p>Students should each have a research journal to record their ideas and observations throughout the inquiry. As they use their journals, students will reveal their thinking and conceptual models. Ensure that your students:</p> <ol style="list-style-type: none"> 1. journal and collect data regularly, 2. post related information on their team blog, and 3. communicate with scientists and peers regularly. <p>The time required for germination experiments will vary depending on the species and/or cultivar being tested, but most crop plants will germinate within one week. At least two weeks should be allowed for data collection in plant growth experiments.</p>	<p>Biological relevance: Students may resist changing biologically irrelevant questions despite encouragement. For example, students are often interested in trials using soda. Since soda is a complex, variable mixture of chemicals that plants rarely encounter in nature, we discourage this type of experiment. Helping students see the environment from a plant’s perspective will improve the scientific soundness of their research plans.</p> <p>Mold: Wet seeds are prone to mold when placed in plastic baggies or in the dark. This is less likely for seeds surface-sterilized for 10 min in 1:9 bleach:water solution with a drop of dish soap. Expect fungal growth even on sterilized seeds if treatments include sugar. Mold does give students a chance to see how the “fuzzy filaments” are aligned and distributed differently from root hairs.</p> <p>Troubleshooting: Helping students realize that experiments don’t always work first time – even for scientists – is important, as problem solving and troubleshooting are highly valued in science-related and other workplaces. However, don’t let students get bogged down in technical debugging at the expense of thinking about the big ideas.</p>

Activity 3: STORYBOARD DISCUSSION (Allow 1 class each to prepare & discuss.)

What is the purpose of a storyboard? Storyboarding consolidates evidence so students can consider how their data fits into their models. By **sharing** their stories and allowing others to **question** their conclusions, students learn to **reconcile** evidence as scientists do. This is sometimes referred to as **scientific thinking**. For general information about the content of a good storyboard and suggestions about how students can use storyboards to build skills in scientific thinking, writing, and discussion, see the document **What is a Storyboard Discussion?**

Preparing storyboards:

Key features for teams to consider as they prepare storyboards for **The Wonder of Seeds** may include:

- Clearly stating whether the team studied **germination**, **plant growth**, or both.
- Describing the team’s thinking about the biological process(es) they studied before *and* after the experiment.
- Summarizing quantitative data from different treatments instead of showing all raw data, such as providing mean and standard deviation for each treatment instead of individual measurements.
 - For example, instead of presenting multiple, individual germination rates for replicates of ten seeds, present the average germination rate for each treatment.
- Presenting clear visual comparisons of data to describe what the team observed.
 - For example, repeatedly measuring seedling height over time might best be graphed with time on the x-axis and height on the y-axis, with each plant or treatment given a unique data marker.
- Finding informative, concrete ways to present qualitative data.
 - For example, photographs may be the simplest way to show differences in seed colors or cotyledon shapes.
- Being able to verbally describe how the information presented in the storyboard connects to **germination** or **plant growth** in addition to being able to develop the storyboard using written and visual information.

Class discussion:

A set of ground rules for productive discussion is provided in **What is a Storyboard Discussion?**

Here, the discussion should center on data to:

- (a) build and revise working models for **germination** and **plant growth** and how environmental or biological factors influence these processes, and
- (b) develop critical thinking skills linking past experience and empirical observations in an experimental context.

Key questions to build inquiry skills:

- What constitutes evidence?
- How does the team’s data fit into its own model of germination or plant growth? Can their model account for the findings of other teams, and can different teams’ models be integrated?
- In what ways was the team’s experimental design limited? Could it be improved or supplemented with another?
- What remains unknown?

Juicy biological questions:

What is the role of the environment or biological variation in germination? In plant growth? How can you tell?

Teams should be able to discuss their answers based partly on their observations during this guided inquiry.

Can germination happen at any time? Is plant growth just a matter of “how fast”? How might conditions for germination and plant growth differ?

Students may not be able to directly answer these questions based on their experiments, but their ideas and models about these processes should gain clarity by discussing them.

Student biases & alternative conceptions:

Inquiry process skills: Students might have selected a question for which they already knew the answer, “adjusted” data to meet their expectations, or concluded that contradictory data confirms their predictions. Weighting assessment towards process skills and away from correct answers may help discourage such biases.

Students may find it difficult to distinguish between what they **think or infer** is happening and what has **actually** happened. Even before the Storyboard phase, provide students with feedback on research journal entries and encourage communication with scientists and peers to assist them in developing this skill.

Biological knowledge: Students commonly believe that:

- All plants have seeds.
- One-seeded fruits (e.g., those from sunflowers) are seeds.^a
- Seeds increase in dry mass during germination.
- All plants have either one or two cotyledons.
- Plants get food or accumulate mass from the soil.
- Sunlight, CO₂, water, and minerals are food.
- Light is helpful but not essential to plant growth.
- Roots are feeding organs.

Some of the above alternative conceptions may have been directly tested in a team experiment. Others might come out in the Storyboard Discussion and can be more quickly addressed in conversation or by comparison to other teams’ findings.

^aA sunflower fruit has one scar on each end. The more prominent scar comes from where the fruit was attached to the receptacle; the second is subtle and indicates the remains of the flower’s style. Sunflower fruits also have two outer layers – the light seed coat is covered by a hard pericarp or “shell” that we remove to eat the “nut” inside. For comparison, consider a watermelon seed. It has a single scar where it was attached to the ovary wall and a one-layered seed coat around the embryo. In grains, the pericarp is often fused to the seed coat.

Unexpected results: If students test fresh and dry weight from the time seeds germinate until the first true leaves appear, they will likely be surprised that dry weight *decreases* during germination and *increases* after greening, while fresh weight continually increases. Before they can photosynthesize, seeds consume their food stores for both formation of new tissues and respiration. The latter results in loss of CO₂, and therefore dry mass, from the seedling.

Product: At the end of the discussion, the class should arrive at a **consensus model** for the role of the environment or biological variation in the regulation of **germination** and/or **plant growth**. The class may also speculate on other conditions promoting **germination** and **growth** to develop a broader understanding of what makes up a plant’s environment.