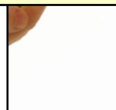
Celery Challenge:
Investigating Water Movement in Plants

Teacher's Guide

Overview



Premise: Many students know that plants require water to live, but fewer understand the processes by which plants take up, transport, and release water. Although plants and plant organs clearly have different structures, students are often surprised to learn that all plant cells are not the same. Understanding that plant cells have different structures and roles within in a plant, and that some cells cannot be fully functional until they are dead, is necessary to link an understanding of plant water use to plant structure. In this module, students work with celery to gain experiential understanding of osmosis, transpiration, and cell and tissue types in the context of questions relating to bending and water transport in this species.

How the Celery Challenge Works: This module is framed as a challenge to cause and explain the most extreme bending in celery petioles (stalks), designed as two guided inquiries and an open inquiry with introductory and concluding class discussions. In the introductory discussion, students imagine a real world scenario about preparing celery the day before a party. Working in small teams, students observe and try to explain two phenomena: (1) the bending of celery stalks soaked in liquids and (2) the concentration of dye in certain cells within celery stalks placed in colored water. Exploring the forms and functions of different tissues and cells allows students to build an understanding of structure-function relationships in biology and lays groundwork for asking and testing a research question in the open-ended inquiry. Options are offered for focusing inquiry on osmosis, transpiration, different cells structures, or combinations of these factors. The final discussion lets teams compare their bending achievements, share their findings, and come to a consensus of what factors cause stalk bending.

Grade levels: High school biology classes are the ideal target for this module. Students at this level have a basic understanding of biology, but complex concepts such as osmosis are still novel and tricky. The module can nevertheless be adapted for middle school and college classes. Many elaborations are appropriate for AP Biology, Botany electives, or undergraduate biology classes.

Class Time: The full investigation will take about two and a half weeks. The initial guided inquiries will take less than one week and can lead to an open inquiry extending at least another week. The concluding Storyboard Discussion requires two or three days, including team preparation time.

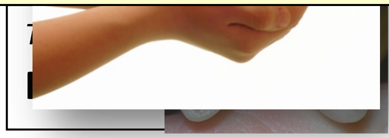
Computer Access: ResearchBlogs are an integral component of the **Celery Challenge**. Ideally, teams should communicate online **every other class session** during guided inquiries and Storyboard Discussion, and **daily** during open inquiry. Minimally, teams should talk with their online mentors throughout the experience, from brainstorming to sense-making. Team blogs require logins.

Crosscutting Concepts & Practices from the Next Generation Science Standards:

CONCEPTS	SCIENTIFIC PRACTICES
• 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 that can be observed at one scale may not be observable at another scale (MS-LS1-1) • Engineering advances have led to important discoveries in virtually every field of science, and scientific discoveries have led to the development of entire industries and engineered systems (MS-LS1-1) • Complex and microscopic structures and systems can be visualized, modeled, and used to describe how their function depends on the relationships among its parts; therefore complex natural and designed structures/systems can be analyzed to determine how they function (MS-LS1-2) • 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 (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions – including energy, matter, and information flows – within and between systems at different scales (HS-LS1-2; HS-LS1-4) • Feedback (negative or positive) can stabilize or destabilize a system (HS-LS1-3)	• Support an argument with evidence, data, or a model (5-LS1-1) • Develop a model to describe phenomena (5-LS2-1; MS-LS2-3) • Science explanations describe the mechanisms for natural events (5-LS2-1) • Conduct an investigation to produce data to serve as the basis for evidence that meet the goals of an investigation (MS-LS1-1) • Develop and use a model to describe phenomena (MS-LS1-2) • Analyze and interpret data to provide evidence for phenomena (MS-LS2-1) • Develop and use a model based on evidence to illustrate the relationships between systems or between components of a system (HS-LS1-2) • Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly (HS-LS1-3) • Scientific inquiry is characterized by a common set of values that include: logical thinking, precision, open-mindedness, objectivity, skepticism, replicability of results, and honest and ethical reporting of findings (HS-LS1-3) • Use a model based on evidence to illustrate the relationships between systems or between components of a system (HS-LS1-4)

Disciplinary Core Ideas from the Next Generation Science Standards:

TRANSPIRATION & OSMOSIS	CELL & TISSUE TYPES
• **Organization for Matter and Energy Flow in Organisms (5-LS1.C)** ○ Plants acquire their material for growth chiefly from air and water (5-LS1-1) • **Cycles of Matter and Energy Transfer in Ecosystems (5-LS2.B; MS-LS2.B)** ○ Matter cycles between the air and soil and among plants, animals and microbes as these organisms live and die. Organisms obtain gases and water from the environment, and release waste matter (gas, liquid, or solid) back into the environment (5-LS2-1) ○ Transfers of matter into and out of the physical environment occur at every level. The atoms that make up the organisms in an ecosystem are cycled repeatedly between the living and nonliving parts of the ecosystem (MS-LS2-3) • **Structure and Function (MS-LS1.A; HS-LS1.A)** ○ Within cells, special structures are responsible for particular functions, and the cell membrane forms the boundary that controls what enters and leaves the cell (MS-LS1-2) ○ Feedback mechanisms maintain a living system's internal conditions within certain limits and mediate behaviors, allowing it to remain alive and functional even as external conditions change within some range. Feedback mechanisms encourage (through positive feedback) or discourage (negative feedback) what is going on inside the living system (HS-LS1-3) • **Interdependent Relationships in Ecosystems (MS-LS2.A)** ○ Organisms, and populations of organisms, are dependent on their environmental interactions both with other living things and with nonliving factors (MS-LS2-1)	• **Structure and Function (MS-LS1.A, HS-LS1.A)** ○ All living things are made up of cells, which is the smallest unit that can be said to be alive. An organism may consist of one single cell (unicellular) or many different numbers and types of cells (multicellular; MS-LS1-1) ○ Multicellular organisms have a hierarchical structural organization, in which any one system is made up of numerous parts and is itself a component of the next level (HS-LS1-2) • **Growth and Development of Organisms (HS-LS1.B)** ○ 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)



Celery Challenge:
Investigating Water Movement in Plants

Suggested Schedule of Activities: A general outline for implementing this module is shown below. None of the individual learning activities are mandatory; rather, they are designed for you to adapt to your classroom. The ScienceTalk is an introductory discussion to stimulate student thinking about water movement in plants. “Party Preparations” and “Celery Sucks!” are both guided inquiries, with the former focusing on osmosis and the latter on transpiration and cell types. The “Maximum Bending Challenge” is an open inquiry that may focus on topics your students are curious about or learning goals you wish to emphasize. Finally, the Storyboard Discussion is a sense-making activity carried out at team and classroom levels, doubling as a summative assessment. Student blogging with scientist mentors and peers is encouraged throughout the module.

Section	Big Question	Learning Activities	Follow-Up	
ScienceTalk	How do plants move water?	Class discussion of Juicy Questions, short video(s).	Student reflections on class discussion; set up teams and ResearchBlogs.	**Blogging with Scientists & Peers**
Party Preparations	How does salt affect the bending of celery petioles?	Guided experiment; record data before and after treatments.	Summarize findings and develop research questions.	
Celery Sucks!	Do all cells move water similarly?	Set up experiments; record data before and after treatments.	Summarize findings and develop research questions.	
Maximum Bending Challenge	What factors can produce the greatest bending in celery petioles?	Select a research question, develop research predictions and experimental design, gain feedback, and carry out experiment.	Analyze data and begin the sense-making process towards storyboard development.	
Storyboard Discussion	What do our observations say about the biology of celery bending?	Teams prepare storyboards and explain them to classmates. Individual teams are critiqued and can refine their ideas.	Develop class consensus on factors involved in celery petiole bending.	

Assessment Schema: The module is designed to assess students *continuously* for changes in understanding and reveal alternate conceptions. Regular online dialogue with scientists, posting of research notebooks and data, and classroom discussions all serve as embedded assessment tools. Final class presentations and discussions, an individual reflection, blogging with the mentor, and the post-experience survey serve as summative assessment tools. If you wish to use an exam for further summative assessment, examples of appropriate questions might include:

- If a student transfers algae cells to a beaker of distilled water, will the algae be hypotonic, hypertonic, or isotonic compared to their surroundings? Explain your answer.
- What is the main function of xylem cells? What is special about their structure that helps them carry out this function?
- What is transpiration?

Additional Resources: ***Celery Challenge Resources*** contains a bibliography of online videos, websites, and peer-reviewed articles, organized by media type. References dealing directly with osmosis and diffusion, transpiration, turgor, and plant cell and tissue types are available, as are references detailing education research on these topics.

Preparation: A minimum of two and a half weeks is needed to complete the full schedule; an additional week may allow deeper exploration or inclusion of an additional topic for open inquiry. We recommend that two inquiries, either both guided, or one guided and one open, be completed together at a minimum. However, any of the inquiries could be conducted as a stand-alone lesson, and either guided inquiry could be simplified to a demonstration.

Please let your scientist mentor(s) know:

- which activities you will be implementing
- your expected start and end dates for interacting with students online
- how frequently your students meet
- how often students will have computer access

Students should work in teams of 2-5. Individual team members are encouraged to post online. The image at left indicates key opportunities for **Team Research Blogging** in the sample schedule on p. 6. Students may blog from school or home, but providing in-class time has advantages.

Suggested plan for classes that meet daily (45 – 60 min periods):

	Mon	Tue	Wed	Thu	Fri
Week 1	**ScienceTalk:** How do plants move water? (+**video**) Form teams and introduce the guided inquiries Party Preparations & Celery Sucks! **Blog:** Register, set up team website, & make first post to scientist. 	***Scientist Prompt:*** What have you learned so far about water in plants? Teams begin Party Preparations inquiry. Teams begin Celery Sucks! inquiry. **Blog:** Reflect on the Science Talk (assessment). 	Teams collect data and write follow-up questions for Party Preparations inquiry. Teams collect data and write follow-up questions for Celery Sucks! inquiry.	Teams select a research question, develop a research prediction, & write up a research plan for the Maximum Bending Challenge. **Blog:** Share guided inquiry findings, research question, prediction, and plan with scientist. 	**Blog:** Read scientist's notes & feedback.  Teams may need to modify the research plan based on feedback. Prepare experimental materials and practice any challenging steps.
Week 2	Set up and begin experiments for the Maximum Bending Challenge. **Blog:** Upload photos & initial data from experiment; contact scientist for questions or troubleshooting. 	Make observations & collect data.	Make observations & collect data. **Blog:** Upload photos & data from on-going experiment; contact scientist for questions or troubleshooting. 	Make observations & collect data.	Last day of data collection; wrap up experiment. **Blog:** Upload photos & data from on-going experiment; contact scientist for questions or troubleshooting. 
Week 3	Summarize data from all inquiries in graphs, drawings, and tables. Work as a team to make sense of the findings from all inquiries.	Prepare Storyboard presentation. **Blog:** Wrap up with research conclusions & ideas for new experiments (summative). 	Present, discuss, and critique Storyboards as a class. Revise conclusions as needed to build a class working model of factors influencing celery bending (summative).		

What factors cause petiole bending in celery?

What types of cells do plants contain?
How do plant cells move around water and solutes?

*planting*science
exploration

GUIDED & OPEN INQUIRIES ON OSMOSIS, TRANSPIRATION, & CELL TYPES

GOALS & TIMELINE

Goals:

- Generate questions and predictions about water movement and bending in celery
- Record accurate qualitative and quantitative observations relating to macro-scale effects of osmosis and transpiration
- Identify different types of celery cells
- Understand that water moves in different ways through different types of plant cells due to their different structures and functions
- Form coherent explanations about celery bending using evidence from multiple sources
- Form coherent explanations about celery bending integrating concepts of osmosis, transpiration and cell type

Sample sequence:

- *Day 1:* ScienceTalk; create teams; set up team ResearchBlog and make first post
- *Days 2-3:* Carry out both guided inquiries; ResearchBlog
- *Days 4-5:* Develop and refine research question and experimental design; ResearchBlog; practice tricky methods
- *Days 5-9:* Carry out experiment, collect data regularly; ResearchBlog
- *Days 10-12:* Analyze data; develop and discuss storyboards; final ResearchBlog

Student Handouts:

Celery Challenge Student's Guide
Brainstorming Page worksheet
About our Research Question worksheet
Experimental Design worksheet
Making Sense of the Data worksheet
Student Roadmap through an Inquiry (*optional*)

Background: Based on past experience, students will generate ideas about water movement in plants and petiole bending in celery and translate them into biologically meaningful conceptual models. Two guided inquiries will help develop student thinking and lay groundwork for a team project to achieve and explain maximum bending in celery petioles. Each team will design and carry out an experiment to answer a research question, then draw conclusions from the data to refine their working model of water movement and celery bending. The teacher's role is to (a) help students develop an experimental design clearly addressing a testable question, (b) guide students in building explanations based on sound reasoning and evidence, while also (c) building connections to concepts such as osmosis and to scientific practices such as changing ideas based on evidence.

Background for Teachers:
Why Does Celery Bend?

Very briefly, celery bends when placed in a liquid solution because the plant organ, a leaf petiole, is made up of different types of cells and tissues, but different cell types respond to available water differently, in a way that is influenced by neighboring cells. **Osmosis is the driving force, but physical resistance is the limiting factor.**

The Response of a Single Cell:

If you put an animal cell, which is bound only by a cell membrane, into distilled water, the water will diffuse across the membrane by osmosis from the region of higher free energy (concentration) of water to the region of lower free energy in the cytoplasm. As a result, the cell swells, the membrane stretches and starts to leak, and eventually the cell bursts as the cytoplasm flows out of the cell into solution. In plant cells, however, the membrane is bound to a cell wall outside it. The cell wall is not necessarily solid! In most plant cells, the cellulose is structured in cell walls like the plastic mesh in produce bags. The mesh is very flexible but has a lot of tensile strength and cannot be pulled apart very easily. The mesh-like cell wall surrounds the membrane the way a mesh bag can hold a plastic bag (Figure 1A). Thus, a plant cell placed into distilled water will still take up water and swell, but it will be restricted by the outer wall, which firmly resists swelling (Figure 1B).

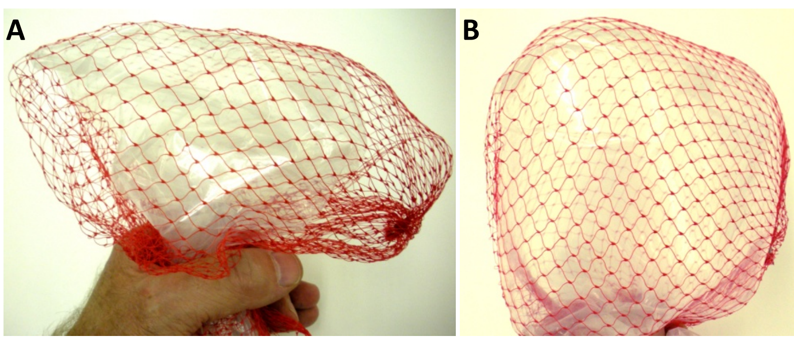


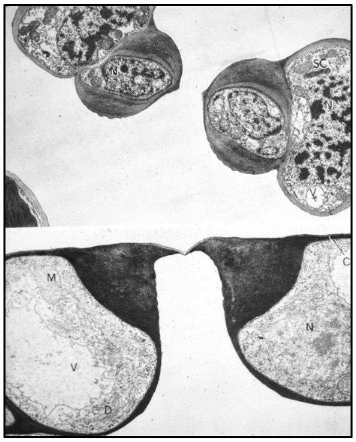
Figure 1. Model of a cell membrane (inner plastic bag) and cellulose cell wall (mesh bag).

In this model, the mesh bag is stretched tight, but individual filaments do not stretch. Cellulose does the same thing in the plant cell wall. The orientation of how the cellulose mesh is laid down lets a cell regulate which way it can stretch when the cell membrane is pressed against the cell wall due to water uptake. As more water pressure builds up inside the cell due to osmosis, the cellulose walls resist stretching more forcefully and the cell becomes firmer. In this state, we say the cell is **turgid**; **turgor pressure** is the force opposing membrane expansion due to increased **osmotic pressure**.

Different Cell and Tissue Types Respond Differently:

Most of the inside of a celery stalk is made up of “ground tissue” or **parenchyma**. The cells are large, with large central vacuoles and thin cellulose walls very similar to the “two bags” model. If a tissue of only parenchyma cells was placed in distilled water, the entire tissue would swell evenly as all of the individual cells took up water and became turgid. If a tissue sample contains any other type of differentiated cell, the positions of those other cells may change the shape of the tissue as it swells.

<u>*Epidermal cells:*</u> Epidermis is a modified type of parenchyma. Three things make it different. First, the outer wall of an epidermal cell, which faces the environment, is usually thicker than its other walls. Second, a tough, waxy cuticle forms on the outside of this thicker outer wall (Figure 2). Third, epidermal



. These
epidermal
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cells can be puzzle-shaped, with adjacent cells interlocking with each other (Figure 3).

Guard cells, a further specialization of epidermal cells, are a microcosm of bending in a celery stalk. The thick cuticle layer acts like a spring and keeps the cells together when little water is available, closing a stomatal pore. When guard cells take up water, their cytoplasm and vacuoles swell. The thick walls can only bend, while the thinner walls away from the stomatal pore stretch. As a result, the pore opens.

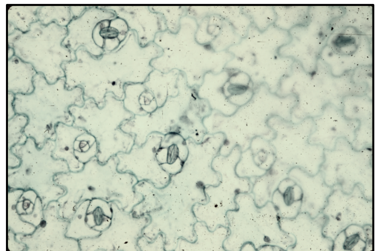

Figure 3. Dark, puzzle-like lines outline epidermal cells on a leaf.

Collenchym celery stalk shaped on on the convex side. Just under the epidermis beneath each ridge is a dense patch of collenchyma. These elongated cells overlap with each other, forming a flexible, cable-like structure. Collenchyma cells are alive at maturity and can grow longer from their tips. Their cellulose cell walls are unevenly thick around the circumference (Figure 4). This pattern of thickening provides good tensile strength, like steel rods placed in reinforced concrete pillars, but still allows for flexibility, like a wire made up of a bundle of many small copper strands. In an unstained section, collenchyma will appear silvery, because water is stored between the mesh-like cellulose fibrils in the cell wall.

Vascular bundles: In all dicot stems, each vascular bundle contains sclerenchyma cells, a type of cell that is dead at maturity. These cells have very thick walls in which the space between cellulose fibers is filled with a hard polymer called lignin. Inside the vascular bundle is mainly a type of sclerenchyma called xylem; outside the bundle is phloem, a special kind of parenchyma. Many bundles also have a bundle cap around the outside of the phloem, which is made of a second type of sclerenchyma called fiber cells (Figure 5). The arrangement of vascular bundles in a dicot's petioles is similar to that in its stem. Vascular bundles in celery petioles are found on the ridged side, deeper than the collenchyma. Each vascular bundle contains a set of xylem cells, with phloem cells separated from the collenchyma by the bundle cap layer.

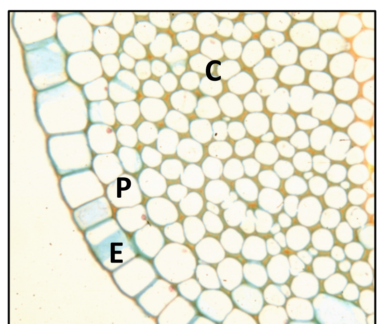

Figure 4. A cross section through a celery stalk ridge consists of an outer epidermis (E), one layer of parenchyma (P), and a patch of collenchyma (C). The greenish-yellow color between collenchyma cells indicates their cell walls.

Cell type and flexibility: Epidermis, collenchyma, and vascular cells all resist stretching more than parenchyma. Epidermal cells are more flexible than collenchyma cells, which, in turn, are less rigid than sclerenchyma. Therefore, a strip of tissue containing one or more of these cell types adjacent to each other, and opposite from parenchyma, will allow less cell swelling than on the parenchyma side of the strip in distilled water, and less cell shrinkage in salt water. As a result, the strip will bend away from the parenchyma in the former case, and towards it in the latter case. This is also described more briefly in the inquiries' **Explanation** sections later in this packet.

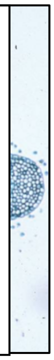

Figure 5. A cross section of a mint stem shows a ring of vascular bundles surrounding parenchyma. Cutting this in half lengthwise would produce a similar structure to that of a celery petiole's ridges.

Beyond Cell Differentiation:

Other factors such as tissue age, environmental conditions, width, source position, and relative proportions of different cell types can all influence the amount of bending in a celery stick. The concepts of osmosis, transpiration, and cell differentiation are key to the overall understanding of celery bending, and students often find it challenging to make connections between them. The possible variables to test in the open inquiry is large enough that even a class lecture on osmosis and distinct cell types will not prevent students from coming up with new ideas for experiments that can build their knowledge well beyond this background information.

ACTIVITY 1: ScienceTalk (Allow 20 min to half a class period)

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Juicy Questions:

- What is happening when a plant wilts?
- How does water enter and move in a plant?
- Does water move the same way in all parts of a plant?
- Can plants grow in salt water?
- How does winter road salting affect plants during spring melting?
- What makes young stems and leaf petioles stiff enough to stand upright or hold a leaf towards light?
- Do plants move? If so, how?
  - What is happening inside the "jaws" of a Venus fly trap when they close or open?
  - What is happening inside leaves or flowers that allow them to close at night and open in daytime?
  - How does sensitive plant close its leaves when touched?
  - Are these movements related?
- Are all parts of a plant the same? All cells in a plant?

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Video Resources:

https://youtu.be/mfDPOfW244k

(3 min)

Water Transport in a Plant describes the challenge tall plants face in transporting water and traces the path of a water molecule through a tree. Narrated by Sir David Attenborough.

https://youtu.be/bm8q5chFyU0

(1.5 min)

Mimosa Pudica (Wild, with Thorns) shows what happens when the leaflets of wild *Mimosa pudica*, or sensitive plant, are touched. The response is due to changes in osmotic potential, and thus turgor pressure, in cells called pulvini.

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Key Features of and Suggestions for the ScienceTalk:

Beyond the Juicy Questions, the key features of a ScienceTalk are shown below in *red*. Suggestions for implementation are shown, but feel free to develop your own approach to fit your classroom.

1. *Engage and explore prior knowledge:*
   - Probe for prior knowledge using the Juicy Questions or ones similar to them.
   - Directly or indirectly introduce the concepts of *osmosis*, *transpiration*, and *cell differentiation*.
     - Student discussion of ideas in their own words is important, so key terms may be introduced after students construct the relevant knowledge.
     - Demonstrating *diffusion* by having students in different parts of the room release air from balloons containing different scents can be a prelude to discussing osmosis.
   - Connect the topic to everyday life and its relevance to society.
     - The scenario in the **Celery Challenge Student's Packet** introduces the first guided inquiry.
     - You could demonstrate osmosis by blowing up a long balloon and adding or releasing air.
       - Taping one side of the balloon before inflation can show how bending occurs when different parts of a plant tissue differ in flexibility.
     - Connecting turgor pressure to plant movements, such as the Venus fly trap "jaws" closing around prey, taps into a common interest in carnivorous plants.
     - Discussing water movement in redwoods taps into student interest in "biggest" things and shows that transpiration moves more water in plants than osmosis or capillary action.
     - Linking transpiration to climate change or food production adds an ecology perspective.

2. *Introduce scientific inquiry concepts:*
   - A discussion of what it means for water to be transported or celery to bend will help students begin developing *working models* for these processes.

  - This is a prelude to figuring out how to recognize these processes during an inquiry.
  - Questions about good *measures* of these processes will support experimental design.
- Brainstorm *factors* that influence water transport or plant bending by thinking about conditions around a plant when they wilt or "perk up."
  - This is a prelude to working out what good control and treatment conditions might be.
  - Asking if some kinds of plants or tissues are more likely to wilt hints at cell differentiation.
- Introduce the essential components of research.
  - Discuss the *inquiry process* in the context of designing experiments, highlighting dependent and independent variables.
  - *Data skills* include careful observing, note taking, data recording, and summarizing data.
  - *Social skills* include teamwork, sharing and building on ideas, and explaining results.

GUIDED INQUIRIES

Purpose: Activities 2 and 3 aim to spur student interest and introduce the concepts of osmosis, transpiration, and cell differentiation. The activities can be carried out in tandem or implemented over three or four days, in either order. Each can be carried out as a guided inquiry or as a demonstration; if desired, one activity can be dropped. As guided inquiries, each uses team observations to introduce a different aspect of cell biology contributing to celery petiole bending. Both include a final brainstorming exercise to stimulate questions that may later become research questions tested in the open inquiry.

ACTIVITY 2: Party Preparations (Allow two or three half-class periods)

Overview: Students observe osmosis and how it influences rigidity of celery cells and tissues. The research question for guided inquiry is **"What causes a plant to bend or move?"** Students will add cut pieces of celery to containers of water containing different amounts of salt. Each piece of celery will be measured, weighed, and qualitatively observed, both before and after soaking in its container overnight. After discussing their observations and what they think may be going on, students record questions based on what they have learned.

Explanation: Tap water is hypotonic relative to living cells, so celery sticks soaked in it will swell, increasing their dimensions, mass, and firmness. Depending on its concentration, salt water will likely be hypertonic relative to the celery cells. Celery sticks soaked in it will lose water, making them flexible or rubbery and reducing dimensions and mass overall. Changes will be negatively proportional to salt concentration, so the saltiest solution will yield the greatest decrease.

enchyma

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Petiole bending relates to both cell type and osmosis. Most of a celery stalk is made up of parenchyma. These cells have large central vacuoles and thin, flexible cellulose walls. If a piece of tissue made only of parenchyma was placed in distilled water, the entire tissue would swell evenly as the cells took up water and became turgid. Other types of cells have reduced flexibility, and will thereby alter the tissue swelling pattern. Epidermal cell walls contain a waxy layer that does not readily stretch; sclerenchyma cells such as xylem contain lignin, limiting their flexibility. In a hypotonic solution like tap water, parenchyma swells more than epidermis or sclerenchyma, so the parenchyma forms the convex side of the curve. In a hypertonic solution like salt water, parenchyma shrinks more, forming the concave side.

Materials (per team)	Logistics
• Enough celery for each team member to cut three 10-15 cm celery sticks • Three containers deep enough to float or cover celery with water • Tap water • Table salt or lab-grade sodium chloride • Balance and weighing paper • A single-edge razor blade, scalpel, or paring knife • Metric ruler • (*Optional*) Vernier calipers • (*Optional*) Protractor • (*Optional*) Digital camera • (*Optional*) Access to a refrigerator	**Detailed procedures** for carrying out experiments and considerations of **lab safety** are described in the ***Celery Challenge* *Student's Guide***. Students should form **teams of 2-4** that can work together throughout the rest of the module. Each student should have a **research journal** to record their ideas and observations. As they use their journals, students will reveal their thinking and conceptual models. Throughout the module, ensure that your students: 1. Journal and collect data regularly, 2. Post related information on their team blog, and 3. Communicate with scientists and peers regularly. **Time Required:** Both days will require about 20 min for student work. Additional time (~15 min) will be necessary for class discussion of the results.

Technical Notes	What To Expect
Salt Solutions: Students may use any salt concentration, as long as the salt dissolves entirely. "Making Chemical Solutions" in **Working with Chemicals** may help students quantify the salt concentration in their solutions. **Temperature:** A refrigerator is not absolutely needed for this inquiry. Temperature will affect the rate, but not extent, of bending. Bending will occur fastest near 25°C and may be measureable within 1-2 hours. A full day of treatment is long enough to eliminate temperature differences as long as the celery was not hot enough to be killed. **Measuring Width:** Width may be difficult to measure, as celery petioles get narrower with height. Sample width will also vary based on how students made their longitudinal cuts. A common approach is to use the minimum width along the axis, regardless of whether it is in the "middle" of the length or skewed	**Qualitative Data:** Most students have poor observational skills that can be improved by encouraging thorough descriptions of qualitative data. For older students, a short paragraph is reasonable. If a digital camera is available, students may add photos to their notes. **Quantitative Data:** Mass will probably be the most precise. You might discuss accuracy and precision as they relate to sample sizes, measuring methods, and tools. **Bending:** Curvature towards the parenchyma may not be apparent if students roughly handle the celery sticks – even college students will play with rubbery celery! Low salt concentrations may be isotonic or even hypotonic relative to celery cells, so it is possible that bending will not occur or will look similar to water-treated samples. **Drawing Conclusions:** Students should be able to link tonicity to changes in the celery sticks' dimensions. They may find it more difficult to link firmness and rubberiness to changes in water content, but returning to demonstrations or the inner tube and tire analogy in the ***Celery Challenge* *Student Packet*** may help. Students often have an idea that the outer, ridged side of the celery is less flexible than its inner side, but they may not

towards one end. Older students may use calipers to measure celery diameters.	be able to fully explain how bending occurs, especially if they are unaware that plant cell types differ in flexibility.

ACTIVITY 3: Celery Sucks! (Allow two or three half-class periods)

Overview: In this activity, students observe transpiration and different tissue types. The research question for guided inquiry is **"Does water move the same way in all parts of a plant?"** This deceptively simple experiment involves placing intact celery petioles, with leaves, into a dye solution. Before and after the stalks stand in the liquid overnight, students make qualitative observations. After soaking, students focus on finding evidence of dye in the plant by external examination and by cutting stalk cross-sections. Students discuss their observations and what they think may be happening, then record questions based on what they have learned.

Explanation: The dye will extend up the celery stalk into the leafy blades, some parts of which may be discolored from the dye. The colored liquid was literally sucked up the hollow xylem cells, primarily due to transpiration. This can only happen if living cells with intact membranes are present in the leaf tissues, where water is released by osmosis into the air spaces between mesophyll cells.

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chyma

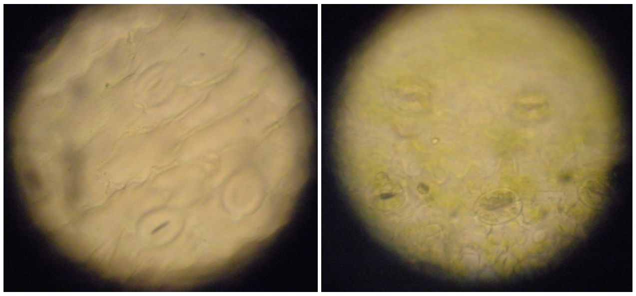
The cells of the cut celery surface submerged in the colored liquid will be stained, but the color will be darkest in a series of spots just inside the ridges on the outside of the celery stalk. Some amount of osmosis occurs in immersed cells due to the hypotonicity of the liquid. A hand lens or dissecting microscope will reveal that the darker spots are associated with the open ends of xylem tubes. In examining cross-sections of the celery stalk above liquid level, students will see that only xylem is stained. Osmosis is limited to immersed cells, while transpiration and the vascular system move most of the water, and therefore dye, up the stalk.

Optional Elaborations: You can expand the guided inquiry or add demonstrations using one or more of the suggestions below. The ***PlantingScience Celery Challenge Toolkit*** details some of the more complex methods, such as making epidermal peels and assembling a potometer.

- Study whether individual vascular bundles supply specific leaf parts or the whole leaf by splitting the celery stalk at the base and placing each side in a different color of liquid.
- Get a cell-scale view of celery petiole tissues by preparing transverse sections of celery stalks, epidermal peels of the inner and outer epidermis, or xylem "strings."
- Experiment with capillary tubes, Pasteur pipettes, or straws to develop working models of xylem cell function relating to capillary action and how it is affected by pressure differentials.
- Calculate water transport rate by incubating celery for a predetermined length of time, such as 30 min, then making sequential, even cross sections up the stalks until dye is no longer visible. Divide the total distance the dye covers by time.
- Track transpiration rate with a potometer by using the distance the meniscus moves over a set period of time to calculate the volume of the cylinder of water the celery consumed.
- Compare water transport in xylem between controls and experimental conditions of differing temperature, humidity, light, and air movement.
- Highlight the role of stomata in transpiration by comparing dye movement in control stalks against those for which one or both sides of the leaves have been coated with Vaseline.
- Use epidermal peels or impressions to examining stomatal density in different celery parts.

- Calculate stomatal density by counting the average number of stomata in the microscope's field of view and dividing by the area of the field of view.
- Calculate total stomata per leaf by multiplying stomatal density by leaf surface area.

- Use the same methods to look for differences in stomatal opening between two treatments.
  - Calculate total stomatal pore area by measuring the average size of the openings from several stomata, then multiplying this by the number of stomata on the leaf.



Impression of upper epidermis (left) and peel of lower epidermis (right) from celery leaflet. Images were taken using 200x magnification. Few stomata are in sharp focus due to specimen curvature.

Materials (per student)

- One celery petiole with intact leaflets
- Container allowing the celery to stand upright
- Tap water
- Food coloring or a biological stain such as safranin, methylene blue, or Congo red
- Single-edged razor blade, scalpel, or knife
- Hand lens or dissecting microscope
- (*Optional*) Poor Man's Microtome (see the ***Celery Challenge Toolkit***)
- (*Optional*) Plastic wrap or butcher paper
- (*Optional*) Masking or clear tape
- (*Optional*) Digital camera

Logistics

Detailed procedures for carrying out experiments and considerations of **lab safety** are described in the ***Celery Challenge Student's Guide***.

Students should work in the **same teams of 2-4** they worked with for the previous inquiry and each keep a research journal, as previously described.

Time Required: Allow about 10-15 min on the first day, which may occur in the same class period as any part of Party Preparations. Allow 20-30 min during the next class period for student observations and 15 min during that period or the next for class discussion and brainstorming questions.

Technical Notes

Plant Material: The celery used here should still have leaves on the end, i.e., do not use trimmed "celery hearts." Fresher celery and younger stalks will generally show greater transpiration rates.

Stalk Support: The celery stalks need to stand overnight in an inch or two of colored liquid. Heavy glasses are ideal for this. For shorter or less sturdy containers, students may have to build supports to hold the stalks upright without tipping.

Dye Color: Red contrasts most strongly with celery tissue and will be easiest to see. Blue may also be suitable. Avoid green and yellow.

What to Expect

Student Observation: Students should be able to easily identify the dye and measure how far it traveled. Some students may need encouragement to explore by cutting the celery instead of just looking at the intact stalk. Students should be able to tell that celery has different cell types from seeing cross-sections.

Drawing Conclusions: Some students may relate the location of dyed tissue beneath the outer ridges of the stalk to the "strings" that get caught between your teeth when eating celery, but fail to connect this to the idea that *xylem cells* have stiff cell walls. Students should be able to connect cell differentiation to differences in water uptake, but many will find

Cutting Stalks: Cleanly cutting across the bottom of the celery stalk ensures even dye uptake. Place the cut end in liquid immediately afterwards to avoid pulling air into the xylem.	it difficult to link their observations to or distinguish among transpiration, osmosis, and capillary action.

ACTIVITY 4: Open Inquiry Lab (Allow one and a half weeks)

Purpose: This open inquiry aims to challenge students to develop a method to achieve the greatest amount of bending in celery petioles. Students develop and carry out their own experiments not only to achieve bending, but to help them explain why it occurs. The open inquiry is intended to encourage students to integrate concepts related to water transport and petiole bending identified during the guided inquiries, and to test any other factors they believe may be involved.

Overview: Broadly, all teams will be asking, **"How far can celery tissues bend?"** and **"What conditions create the most bending?"** Each team will select a narrower, testable research question based on one or more of the brainstorming questions they wrote down after the guided inquiries. From this, teams will make a research prediction and develop an appropriate experimental design. Methods can incorporate and build on previous experiences in the module; use of the ***Celery Challenge Toolkit*** is encouraged. Teams refine and carry out their experiments, collecting data to quantify bending. Data and observations will feed into each team's storyboard presentation to explain why their celery did or did not bend as much as they had anticipated.

Explanation: Students must decide how to bend the celery, keeping in mind that different cell types respond differently to osmosis due to their structural features. The plant response always comes back to the osmotic response of parenchyma cells to the soaking solution, and to the kinds and positions of specialized cells that physically resist the enlargement (or shrinkage) of the parenchyma. Xylem and collenchyma strands on the ridged side of the stalk function like steel reinforcing bars in concrete or the fibers in fiberglass. On their own they can bend, but they resist stretching. Even if thin-walled parenchyma cells fill with water, they will not be able to elongate if xylem fibers and collenchymas are adjoining them, because the latter are not as flexible. The smooth side of the stalk lacks resistance, so the parenchyma on this side can elongate, thereby bending the stalk.

The response of a given piece of celery will also depend on other factors. In general, younger tissues are more responsive than older ones, because they haven't finished developing and are more flexible. Thus, older stalks from the outside of a bunch will likely bend less than younger ones on the inside. As another example, pieces cut from just beneath the leaflets will also respond differently from sections taken just above the base. The cross-sectional shape of the piece, and whether or not it goes all the way from the inner to the outer epidermis, will also influence how much bending occurs.

Optional Elaborations: Teams may wish to use methods from the ***PlantingScience Celery Challenge Toolkit*** to collect data. If students need more scaffolding to integrate the multiple concepts in the module, you may want to allow time to analyze and synthesize findings from the guided inquiries, directly discussing osmosis and different cell types prior to beginning the open inquiry. You may also guide research questions to focus on specific topics of interest.

- To study relationships between cell differentiation and cell function:
    - Observe thin cross-sections of stalk under a microscope to identify and measure which cells swell or shrink in different solutions

- Cut or shave the stalk to produce test samples missing parenchyma, xylem, collenchyma, epidermis, or combinations thereof
- Studying types of water movement could involve comparing parenchyma to xylem in their capacities for osmosis or capillary transport
- Study the effects of environment, such as temperature, humidity, light, or air movement
- Study different salt concentrations from previous tests or different kinds of solutes
- Study effects of the plant hormone auxin, which is related to bending during cell elongation
- To study tissue type, position, and development:
  - Remove epidermis from the inner, smooth side or outer, ridged side of the stalk
  - Test vertical source of samples, with some sticks from more basal (flared) and others from more aerial ("C"-shaped) tissues
  - Test lateral source of samples, with some sticks from the middle of the stalk (cut on both sides), and some from one edge, so the epidermis forms one curved piece
  - Test the number of ridges in a celery stick sample
  - Vary the cross-section of the sample, e.g., wider away from or adjacent to the ridges
  - Test older, outer celery stalks against younger, inner stalks of the same size

Materials (per team)

- Celery petioles with intact leaflets for each student to make 3 or more ~10-15 cm sticks
- At least 3 containers
- Tap or distilled water
- Salt or other solute for solutions
- Digital balance
- Scoopula or spoon and weighing paper
- Single-edge razor blade, scalpel, or paring knife
- Metric ruler or Vernier caliper
- Protractor to measure bending angle
- Food coloring or biological stain
- Hand lens and/or dissecting microscope
- (*Optional*) Digital camera
- (*Optional*) ImageJ software

Logistics

Detailed procedures for carrying out experiments and considerations of **lab safety** are described in the ***Celery Challenge* *Student's Guide***.

Students should work in the **same teams of 2-4** as they did for previous inquiries; keeping a research journal is critical for the open inquiry.

Time Required: Allow 5-8 class hours for the full inquiry, which includes developing and revising the research plan, practicing any tricky techniques, setting up the experiment, making measurements and qualitative observations, and summarizing data.

Technical Notes

Removing Ridges: Some students may want to make samples by removing the tough strands of xylem and collenchyma making up the outer ridges of the celery stalk. Older students may cut out ridges with a blade, while younger students can use their fingernails to pick them out of one end of the stalk, then peel them down the length of the stalk, as shown below.

What to Expect

Research Question: The open inquiry offers diverse avenues to investigate structural, physiological, and environmental relationships. Student questions will likely fall along the lines of:

- *What happens if we remove all the ridges?*
- *Will we get more bending if we cover all the stomata?*
- *How much will celery bend if we soak it in hot water?*

Asking biologically relevant questions may be a challenge, so having a peer-review phase requiring teacher approval before starting the experiment can be valuable.

Hormone Treatment: If students want to try to induce bending with plant hormones, applying a paste of auxin and lanolin to one side of the celery stalk is a reasonable method. Since it affects actively elongating cells, young, growing stalks near the center of the bunch are the most likely to visibly respond.

Confounding Factors: Students will probably not realize the difficulty of isolating a single environmental factor. For instance, using a fan to increase air flow may indirectly increase concentration of a salt solution. Increasing light intensity with a lamp may also increase air temperature. Don't worry about this at the start; such details can be highlighted in the Storyboard Discussion, especially if different teams have carried out experiments on related factors.

Experimental Methods: Teams should choose their own variables to test and figure out their own ways of gathering data. If teams have difficulty with technical methods, don't let them get bogged down in troubleshooting at the expense of the big ideas.

Student Observation: Middle and high school students may have difficulty identifying what they see when examining cells with a microscope. The ***Celery Challenge Student's Packet*** and pp. 8-10 here include some sample images for reference.

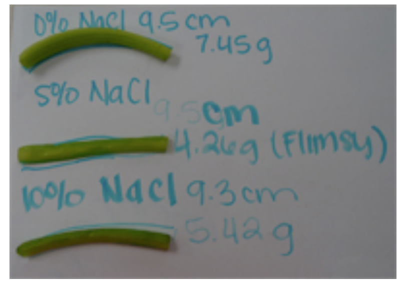
Alternate Conceptions: Students commonly believe:
- The terms iso-, hypo- and hypertonic refer to water content, not solute concentration.
- All plant species have similar numbers of stomata.
- Stomata occur only on lower surfaces of leaves.
- Most water taken in through roots is consumed by the plants, not lost through transpiration.
- High humidity increases transpiration.

Most of these misconceptions can be directly addressed through experimentation. Inaccurate definitions are best addressed in discussion.

ACTIVITY 5: Storyboard Discussion (Allow two full class periods)

Objective: The overall goal of the Storyboard Discussion is to have students make sense of what their data mean, focusing on the question, **"Why does the celery bend?"** Teams should have a full class period to work out their answer to this question and to develop a storyboard, a visual representation of their work similar to a scientific poster. Each team will present their storyboard to the whole class, so all team members should be able to discuss its contents. Teams will critique each other's storyboards and work together to develop a comprehensive answer to the above question.

Storyboard Preparation: At this point, teams will have collected qualitative and quantitative data in up to three inquiries. Ideally, teams will already have summarized their own data in digital images, graphs, tables, and short descriptive notes. They will likely find it fairly easy to present these data, as in the photo at right.



To prepare for the class discussion, allow teams to work together during one class period to make sense of their data and observations. As they do this, they should create a visual and written narrative of their research question(s), how they tested the question(s), how they knew their experiment(s) worked, what data and observations they made, and how these helped answer their question(s). If teams will present multiple inquiries in a single storyboard, remind them to clearly delineate each one. Older students could also show how guided inquiries informed the open inquiry, such as by brainstorming a question or identifying test variables.

Teams will benefit from scientist mentors' guidance as they look for explanatory mechanisms for their observations. Two key questions to assist students with sense-making are **"Why do we think the conditions we used created the most bending?"** and **"What qualitative and quantitative data are evidence for our reasoning?"** The first question can help teams link experimental conditions to concepts of transpiration, osmosis, changes in cell size, cell types, and other factors tested. The second helps each team base its arguments in data from all inquiries the team has completed.

Class Discussion: Allow a full class period for each team to present its storyboard, including time for the rest of the class to ask questions and provide feedback about the presentation, storyboard, or team conclusions. Facilitate comparisons among different treatment conditions, encouraging students to identify which factors caused the most petiole bending. You might also ask what students would expect to see if they carried out an experiment consisting of two different factors that both caused bending. The discussion can be drawn to a close by developing an overall **working model** of petiole bending in celery that accounts for the results of all teams' experimental conditions.

To summarize the overall findings, you may wish to have each team record on a notecard the amount and direction of bending they observed in their most successful treatment and what the conditions were for that treatment. The top three teams with (a) the greatest amount of bending and (b) a clear explanation as to how the treatment caused bending can be awarded additional points for "winning" the Celery Challenge. If the three teams used different treatments to achieve the observed bending, this provides a second route to address the role of multiple factors in celery bending.

Students will become quickly aware, if they did not know already, that different teams tested different factors. If any teams have factors related to or confounding those tested by another team, they may see that "their" variable could also have been involved in someone else's experiment. If students do not bring up this point themselves, raise it yourself to set the stage for teams to discuss how they might redesign a future experiment to eliminate the confounding variables. Searching for and eliminating alternative explanations is a critical feature of science that is usually overlooked until graduate school!

What to Expect: Students have likely taken on the challenge to bend celery with gusto and succeeded. The greater challenge comes in explaining what is happening. Integrating multiple concepts will likely be a key difficulty. For example, students might recognize that xylem strands or ridges in the stalk affect bending, but they are unlikely to recognize that the xylem resists stretching or to relate this to osmosis. Attend to students' thought processes to shift assessment from a right-answer orientation towards an emphasis on reasoning. We often make assumptions about students' ideas and connect concepts in ways novice learners cannot. Careful probing can upturn our assumptions and those of our students – such as when students ask each team questions here.

Additional Information: A description of the contents of a storyboard, how to integrate writing and discussion into a presentation, how to focus the class discussion, ground rules for a productive discussion, and final outcome are all provided in the document ***What is a Storyboard Discussion?***