SHORT FILMS ABOUT CHEMISTRY

Driving Reactions

IN THE CLASSROOM

CLASSROOM LESSON PLAN
GRADES 9–12

CHEMISTRY SHORTS™

Driving Reactions

CLASSROOM LESSON

Overview

This lesson plan contains student activities, teacher notes, and additional resource suggestions that are intended for use with the *Chemistry Shorts*™ film "Driving Reactions." The film is freely available for viewing online either at the link above or http://chemistryshorts.org. The activities stand alone, with no additional background material needed. The activities are aimed at grades 9–12. Teachers may adjust or extend discussion of the chemistry involved depending on the students' level. The plan is designed for use as a complete package, although teachers may choose individual activities.

The lesson and materials are suitable for both in-person and virtual classrooms.

Classroom Materials

- Method for viewing *Chemistry Shorts*™ film "Driving Reactions."(9 min, 17 sec)
- Student Activity handouts (paper or digital copies)

Student Activities with Estimated Times

Pre-Class Activity Designing for the Future	(10–15 min.)
In-Class Activity Enzymes and Chemistry	(15–20 min.)
In-Class Activity Directed Evolution (including watching the film)	(20–25 min.)
In-Class Activity Polymer Chemistry	(5–10 min.)
After-Class Activity The Future of Directed Evolution	(5–10 min.)

Related Standards

NGSS HS-PS1-5
Apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs.

NGSS HS-PS2-6
Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.

NGSS HS-LS1-1
Construct an explanation based on evidence for how the structure of DNA determines the structure of proteins, which carry out the essential functions of life through systems of specialized cells.

NGSS HS-ESS3-4
Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.

NGSS MS-LS3-1
Develop and use a model to describe why structural changes to genes (mutations) located on chromosomes may affect proteins and may result in harmful, beneficial, or neutral effects to the structure and function of the organism.

NGSS MS-LS4-5
Gather and synthesize information about the technologies that have changed the way humans influence the inheritance of desired traits in organisms.

CCSS.ELA-Literacy.RST.9-10.5
Analyze the structure of the relationships among concepts in a text, including relationships among key terms (e.g., *force, friction, reaction force, energy*).

CCSS.ELA-Literacy.RST.9-10.4 & 11-12.4
Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 9-10 texts and topics/grades 11-12 texts and topics.

CCSS.ELA-Literacy.RST.11-12.2
Determine the central idea of conclusions of a text; summarize complex concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms.

CCSS.ELA-Literacy.RST.11-12.7
Integrate and evaluate multiple sources of information presented in diverse formats and media (e.g., quantitative data, video, multimedia) in order to address a question or solve a problem.

CCSS.ELA-Literacy.W.11-12.2
Write informative/explanatory texts to examine a topic and convey ideas, concepts, and information through the selection, organization, and analysis of relevant content.

Pre-Class Activity Teacher Notes
Meeting the World's Challenges

Question 3
The example answer given in the Answer Key is explored in the *Chemistry Shorts*™ film "Untapped Potential" and its accompanying lesson plan.

In-Class Activity Teacher Notes
Enzymes and Chemistry

Question 2, part a
Enzymes are catalysts. However, that does not mean that all catalysts are enzymes. For example, students may be familiar with catalytic converters in vehicles. They use metal catalysts, not enzymes. Further background on the chemistry of catalytic converters is in the ACS Reactions video "Catalytic Converter Stolen? Here's Why."

Question 2, part b
https://www.acs.org/greenchemistry/principles/12-principles-of-green-chemistry.html and https://www.compoundchem.com/2015/09/24/green-chemistry/ both summarize the 12 principles of green chemistry. Students could analyze each principle and decide if it applies to the use of enzymes.

Question 3, parts a and b
All of the compounds involved in the reaction would be 3-dimensional rather than 2-dimensional on the page. Instructors could show students the animation at the beginning of the video "How Enzymes Work" from RCSB Protein Data Bank. It is an animation of what many enzymes in a cell might look like as they work.

In-Class Activity Teacher Notes
Directed Evolution

A copy of Dr. Frances Arnold's Nobel Prize lecture on directed evolution is available at https://www.nobelprize.org/prizes/chemistry/2018/arnold/lecture/

Question 1
Additional background reading on how a cell moves from DNA to protein, along with mutations having different effects or no effects is at https://bioprinciples.biosci.gatech.edu/module-4-genes-and-genomes/06-gene-expression/

Instructors could share specific situations of DNA mutations, such as Shar Pei dogs, extra-toed cats, red hair, and cystic fibrosis. The site highlights the protein and the difference in the DNA that encoded it.
https://learn.genetics.utah.edu/content/basics/outcomes/

Question 3, part a
Background on the enzyme's discovery and what others thought of its potential is at:

- https://www.upi.com/Science_News/2016/03/11/Newfound-bacteria-can-eat-plastic/2261457705398/
- https://www.upworthy.com/accident-resulted-in-a-plastic-eating-mutant-that-just-might-save-us-all-rp
- https://www.science.org/doi/10.1126/science.aad6359

In-Class Activity Teacher Notes
Polymer Chemistry

Question 1
One way to visually demonstrate a model similar to a chain of linked monomers is with a bead necklace that has been cut apart at one location, creating one long piece. A video showing a much longer length of beads being pulled by gravity from a beaker is from Sick Science! (https://youtu.be/m-88M75_PCI)

Question 3
For further background information, a 2013 press release about the change in resin identification code triangle design is at https://newsroom.astm.org/astm-plastics-committee-releases-major-revisions-resin-identification-code-ric-standard

A common hands-on polymer activity is to make slime. One procedure is available from the Royal Society of Chemistry.
(https://edu.rsc.org/experiments/pva-polymer-slime/756.article)

After-Class Activity Teacher Notes
The Future of Directed Evolution

Question 1

If students also did the Pre-Class Activity “Meeting the World’s Challenges,” they could revisit their answer to its Question 3. How could directed evolution support the challenge they listed?

Question 3

For further background, instructors could read the blog post at the link below that compares traditional directed evolution with machine learning-assisted directed evolution. Although it uses some specialized language, much of it is also written informally. (https://ericmjl.github.io/blog/2021/9/12/machine-directed-evolution/)

Name ______________________________ Date ______________

Pre-Class Activity
Designing for the Future

1. Design your perfect pet. If you were to have a dog, which properties or characteristics would best suit your situation and preferences?

a. Fill in the table below.

Characteristic	Possibilities	My Choice
Fur shedding	*Minimal shedding, some shedding, any amount of shedding*	
Fur texture		
Fur color		
Fur length		
Eye color		
Overall size		
Weight range		
Temperament		
Trainability		

Name ______________________ Date ____________

Pre-Class Activity
Designing for the Future (continued)

b. Using science, how could you achieve the specific set of properties you described in the table? Estimate how long this process might take.

2. Natural mutations, or changes in a DNA sequence, can occur in animals and other organisms. These can result in new properties—some desired, some not. Researchers use directed evolution, a process of randomly mutating DNA and screening for properties they want over and over, to make proteins with new, desirable properties.

Directed evolution was used to modify a protein that can turn a plastic back into the materials originally used to make it. Describe a possible application for this protein.

3. Think of a challenge the world faces that you think science could help to solve.

a. Describe the challenge and how it has affected or will likely affect you.

Name ______________________________ Date ________________

Pre-Class Activity
Designing for the Future (continued)

b. How has science, and chemistry specifically, dealt with this challenge already, or how could it possibly help to solve it in the future?

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Name ______________________________ Date ______________

In-Class Activity
Enzymes and Chemistry

Enzymes are chemical tools that can serve us in different ways. They support processes in our bodies, like respiration, muscle contraction, and digestion. Enzymes can even be designed to function how we would like them to—potentially solving some of the world's challenges.

1. Early in the film "Driving Reactions," how does Dr. Alper define an enzyme?

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2. For a chemical reaction to occur, reactants need to come together in the correct orientation with enough energy to react. Some reactions would take much longer than desirable if left to occur on their own. An enzyme makes the environment more favorable for the reaction to happen, lowering the activation energy to start the reaction. The enzyme can increase the rate of the reaction, so it can occur more quickly. It is not used up in the process.

a. An enzyme serves as a catalyst for a reaction. A non-chemistry definition of the word catalyst is "a person or thing that causes a change." Describe how this non-chemistry definition relates to the chemical function of an enzyme.

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b. One of the 12 principles of green chemistry is to use catalysts, including enzymes, in reactions. Based on the description of an enzyme, why is its use more sustainable?

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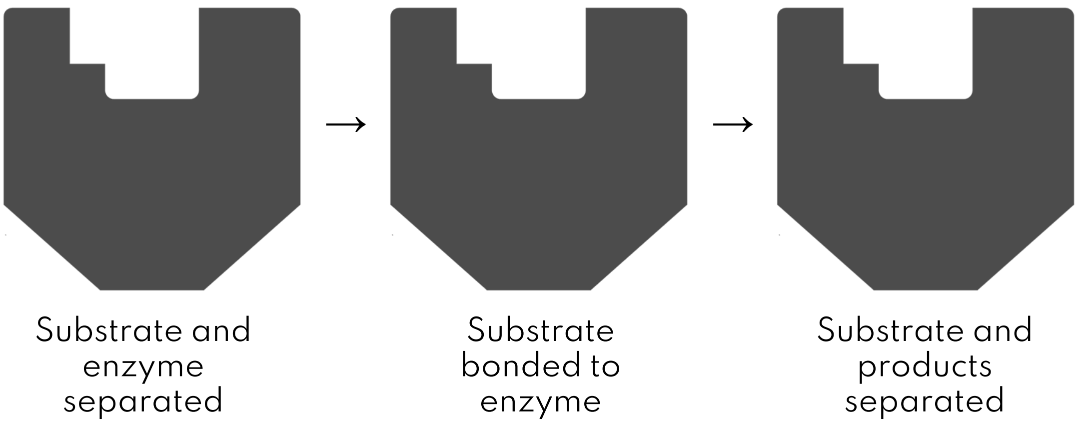
Name ______________________________ Date ________________

In-Class Activity
Enzymes and Chemistry (continued)

3. The active site of an enzyme is the location where substrates, or reactants, bind and undergo catalysis. This active site is complementary in shape to a particular substrate.

a. The repeated irregular shape below represents an imaginary enzyme that catalyzes a decomposition reaction (accelerates breaking the substrate into two or more products). Its active site is the shaped pocket and top. Read the label for each section and draw substrates and products that could fit this enzyme.



b. Draw a shape to represent a compound below that would not be able to be catalyzed by this imaginary generic enzyme. Explain.

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Name ________________________________ Date ________________

In-Class Activity
Enzymes and Chemistry (continued)

c. Predict what would happen to the rate of catalysis with each of the changes below. Include your reasoning.

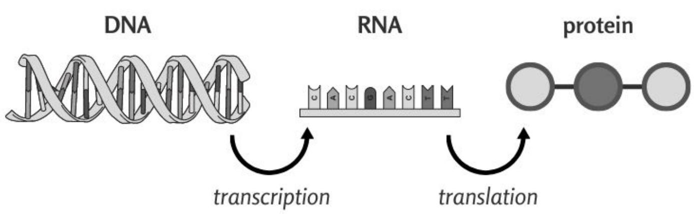
Change	Rate: increase / decrease / same	Reasoning
Solution temperature increases, causing the enzyme structure to unravel		
Compound similar to the substrate binds to the enzyme, blocking the active site		
Additional small compound binds near the active site, causing the fit and binding of the substrate in the active site to be slightly improved.		

Name ______________________________ Date ______________

In-Class Activity
Directed Evolution

Nature provides us with useful compounds, including enzymes. Sometimes, we might want to tailor those enzymes for a specific use or to function in a particular environment. The tool of directed evolution can get us there.

1. Over time, through evolution, nature has developed versions of enzymes that function better than others. This happens through mutations in DNA in a cell. The pathway from DNA to the proteins that make up enzymes has multiple steps. A simplified description is information in DNA is transcribed into RNA, then translated into a protein that forms the enzyme.



a. Answer this question using the film as a guide: In directed evolution, what do researchers first do to the piece of DNA that encodes an enzyme to work toward a new version of that enzyme?

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b. What do they do with the DNA afterward to produce the protein?

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c. Will all mutations result in improvements to the protein? Explain.

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Name ____ Date ____________________

In-Class Activity
Directed Evolution (continued)

2. The film compares the process of directed evolution to a demolition derby of cars.
   a. Fill in the remaining parts of the analogy based on the film.

Detail of Demolition Derby	Associated Detail of Directed Evolution
Ordinary car	*Original enzyme of interest from nature*
Beginning field of tricked-out cars	
Some cars beat other cars	
Remove demolished cars from competition and upgrade remaining cars	
One winner	

   b. In a real demolition derby, pit crews might repair parts on vehicles, but don't add new "tricked-out" modifications between rounds. How is this part of the analogy different from what researchers do with enzymes that "beat other enzymes" in a round of directed evolution before the next round?

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Name ______________________ Date ____________

In-Class Activity
Directed Evolution (continued)

3. PETase is an enzyme that is able to break down bonds in plastic, specifically in polyethylene terephthalate, or PET.

a. Using the film, briefly describe how this enzyme was first discovered.

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b. PETase from nature is described as having "really low level activity," meaning it worked slowly and in limited environments. Using the film, outline the steps of how Dr. Alper used directed evolution to create the enzyme FAST-PETase, which stands for Functional, Active, Stable, and Tolerant PETase.

Original Enzyme	Directed Evolution Steps	Final Enzyme
PETase		Functional, Active, Stable, and Tolerant PETase

Name ______________________________ Date ______________

In-Class Activity
Polymer Chemistry

Polymers are an integral part of our world. They are in common items, such as food storage containers, athletic clothing, paper, and even toys like slime. Some are part of our bodies, including DNA and hair.

1. The word polymer breaks into *poly* meaning "many" and *mer* meaning "part." A polymer is a large molecule made of smaller repeating units, tens to hundreds to thousands of them connected in a chain-like structure. These units are called monomers. Consider the parts of the word monomer. How does the name monomer relate to its role in the polymer?

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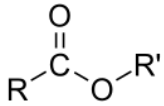
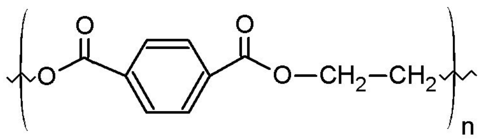
2. Polyethylene terephthalate, also referred to as PET or PETE, is a polymer that uses two different kinds of monomers: terephthalic acid and ethylene glycol. These react to form an ester. Esters are organic compounds and have the basic form (see right) where R and R' represent additional hydrocarbon parts of the molecule.

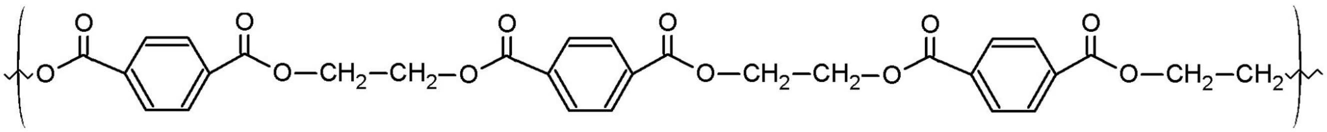


The ester below is the repeating unit of PET, making it a polyester. The parentheses and zigzag lines at both ends show that the structure continues with this repeating unit. A number could replace *n* to show how many units there are.



a. In the longer PET structure below, circle each of these repeating units.

b. How many monomers are in this short section of polymer? ______________



Name ______________________________ Date ______________

In-Class Activity
Polymer Chemistry (continued)

3. In the U.S., if you look on an item made of PET/PETE, you will probably find the resin identification code 1 inside a triangle (see below). This system was developed in the late 1980s as a consistent ID system for manufacturers and recyclers, but not of an item's recyclability. The numbers go from 1 to 7 and often include a letter abbreviation. Resin numbers 1 (polyethylene terephthalate), 2 (high-density polyethylene), and 5 (polypropylene) are plastics that are most often accepted at recycling facilities. Others are currently not widely recyclable.

a. In 2013, the design was changed from the arrow-based triangle on the left to the solid triangle on the right. What do you most commonly associate with the triangle style on the left?

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b. Discuss how the triangle on the right could be considered to be a better representation for consumers to see on a plastic item than the arrow-based triangle.

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Name ______________________________ Date ____________

After-Class Activity
The Future of Directed Evolution

1. What existing or potential future problem could directed evolution and enzymes potentially solve?

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2. The enzyme FAST-PETase is able to break down limited amounts of the plastic polyethylene terephthalate (PET) in a laboratory setting. Describe things that you think would need to be considered and worked out before it is able to be used widely in recycling facilities, including in your community.

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Name ______________________ Date ____________

After-Class Activity
The Future of Directed Evolution (continued)

3. Dr. Alper's team used machine learning to do part of the process of directed evolution virtually. A computer can:

- be shown many enzymes and told what they do
- learn how each shape and structure in an enzyme contributes to its function
- model different combinations of mutations to simulate how they might change an enzyme's efficiency and effectiveness

Then, that information can guide which mutated DNA is actually made for testing.

a. What is a possible benefit to using machine learning-assisted directed evolution? What is a possible challenge?

b. What else could machine learning be used to predict?
(Looking for inspiration? See what these teenaged researchers have created at https://www.societyforscience.org/blog/teen-scientists-and-engineers-win-5-million-at-largest-global-high-school-stem-competition/)

Chemistry Shorts™ is a film series that communicates the breadth and depth of chemistry's impact on humankind in an approachable manner, sponsored by the Camille and Henry Dreyfus Foundation. These films will celebrate the science and the people who share a passion for the vital role chemistry plays in the biggest issues, including human health, renewable energy, the nature of life, sustainability, new materials, and climate change. Each film incorporates a lesson plan that offers ideas for ways they may be incorporated into the classroom. We welcome your feedback at: chemistryshorts.org.

SHORT FILMS ABOUT CHEMISTRY

SHORT FILMS ABOUT CHEMISTRY

Driving Reactions

IN THE LABORATORY

LAB EXPERIMENT
GRADES 9–12

CHEMISTRY SHORTS™

Overview

This lab experiment complements the *Chemistry Shorts* ™ film "Driving Reactions". The film is freely available for viewing online either at the link above or http://chemistryshorts.org. The experiment is aimed at grades 9–12 and potentially above. Teachers may adjust or extend discussion of the chemistry involved depending on the students' level.

Materials

- Student Handout
- Experiment materials per student pair/group
  - Yellow banana with very few or no brown spots
  - Round wooden toothpicks
  - Ruler
  - Timer
  - Cutting board
  - Knife
  - Tap water
  - Small bowl
  - Fork
  - Paper towel

Estimated Times

Part 1	5-10 min.
Part 2	10-15 min.
Part 3	10-15 min.
Total	**25-40 min.**

Related Standards

NGSS HS-ESS3-4
Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.

NGSS HS-ETS1-2
Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

CCSS.ELA-Literacy.W.11-12.2
Write informative/explanatory texts to examine a topic and convey ideas, concepts, and information through the selection, organization, and analysis of relevant content.

Driving Reactions

STUDENT HANDOUT

Name ______________________________ Date ______________

The Browning of Bananas

What's your banana preference? Spots or no spots?

What is needed for brown areas to appear on the fruit? In this experiment, you will investigate what makes brown spots form, discuss the possible drawbacks and benefits of browning, and consider how the banana's chemistry might be modified for additional uses.

> How long do you estimate it would take for the banana on the left to brown like the one on the right? Do you think it would be possible to speed up the process? Why/why not?

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Materials

- ❏ Yellow banana with very few or no brown spots
- ❏ Round wooden toothpicks
- ❏ Ruler
- ❏ Timer
- ❏ Cutting board
- ❏ Knife
- ❏ Tap water
- ❏ Small bowl
- ❏ Fork
- ❏ Paper towel

Safety

Do not taste or consume any of the banana. Use caution with knife and when using toothpicks to pierce banana.

Name ______________________________ Date ____________

The Browning of Bananas (continued)

Procedure

Part 1

1) Using the sharp tip of a round wooden toothpick, poke multiple holes in the bottom ~3 cm of the skin of an unpeeled yellow banana with few or no brown spots, You could create a shape or design using the holes. Keep the holes shallow, trying not to pierce through to the fruit underneath.

2) Observe the holes and the toothpick tip for 1–2 min. Record your observations.

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3) With a cutting board and knife, cut off the bottom ~3 cm of the banana where you made holes. Set aside for later observation. Cut off another 3-cm piece (fruit with skin still on) from the already-cut end of the rest of the banana for Part 2.

Name ______________________________ Date ________________

The Browning of Bananas (continued)

Procedure

Part 2

1) Take the piece of banana from step 3 and remove the skin. Cut the skin in half.

2) With an unused round toothpick, create a shallow groove on the surface of one of the parts of the banana pieces (inner surface of skin, outer surface of skin, or fruit) by dragging the tip over it. Save the toothpick to observe. Repeat with new toothpicks and the other two parts of the banana pieces. Observe the grooves and tips of the toothpicks for 1–2 min. Record your observations in the table.

	Outer yellow skin	Inner skin	Fruit
Groove			
Toothpick tip			

Driving Reactions

STUDENT HANDOUT

Name ______________________________ Date ______________

The Browning of Bananas (continued)

Procedure

Part 3

6) Fill a small bowl half full of room temperature tap water.
7) With a cutting board and knife, cut an additional ~3-cm banana piece. Remove the skin. Cut the skin in half.
8) With an unused round toothpick, create a shallow groove on the outer yellow skin of one of the pieces by dragging the tip over it. Set the skin aside to observe.
9) Place the second piece of skin under the water in the small bowl, with the outer yellow skin facing up. With an unused round toothpick, create a shallow groove on the outer yellow skin of one of the pieces by dragging the tip over it. Rest the tines of a fork on part of the skin to hold it underwater, leaving the groove visible.
10) Observe both grooves for 1–2 min.
11) Remove the second piece from the bowl. Gently blot any water from the outer yellow skin with a paper towel. Observe and record your observations for 5 min.
12) Return to the banana piece you made your design on in Part 1. Record any further changes.

	No water	Under Water	Under water, then above water.
Outer Yellow Skin			

Name ______________________________ Date ______________

The Browning of Bananas (continued)

Questions

1) Compare your observations from step 2 with the answer you gave to the questions in the lab introduction.

2) From your observations in Parts 2 and 3, is the compound that causes browning present in all three parts of the banana? In any parts where it is present, is it present in similar amounts? What had to be present to the browning to occur? Explain your reasoning.

3) For the brown color to form, an enzyme in the banana first catalyzes the oxidation of other compounds in the banana. The enzyme increases the rate of the oxidation reaction, so it can occur more quickly. The resulting compounds then react to form brown pigments called melanins.

   a. The enzyme and the compounds it reacts with are both in a banana cell, but are originally separated in the cell. What did you do in the experiment so the enzyme came together with the compounds?

Name ______________________________ Date ________________

The Browning of Bananas (continued)

Questions

b. What are things that could happen to bananas as they travel from where they grow to your kitchen that would cause the enzyme and compounds to come together in a cell?

4) Consider how the enzyme's chemistry might be modified for specific situations.

a. From the viewpoint of a company that ships bananas to worldwide markets, would it be more beneficial to have bananas with a version of this enzyme that is very efficient or less efficient? Why?

b. Biosensors that use enzymes to detect specific chemicals have been developed for quality analysis of pharmaceuticals. For example, the browning enzyme has been used in a biosensor to compare the quantity of acetaminophen actually present in pills compared to the amount they are meant to contain. Biosensors can be a less expensive, faster method of analysis.

To prepare a biosensor, would it be more beneficial to have a version of this enzyme that is very efficient or less efficient? Why?

Name ______________________________ Date ______________

The Browning of Bananas (continued)

Questions

c. Based on your viewing of the film "Driving Reactions," briefly describe how directed evolution could be used to tailor this enzyme to one of these or another purpose.

Teacher Notes

Sample Observations

Testing showed the following results:

- Part 1, Step 2: Holes began to turn brown quickly. By the time the final holes of the design were being made, the first holes were already darkening. The holes gradually darkened over time, along with tip of the toothpick.
- Part 2, Step 5

	Outer yellow skin	Inner skin	Fruit
Groove	Quickly turned brown to dark-brown	Had some color change, turning darker. Not as much color change as outer skin	No noticeable change
Toothpick tip	Quickly turned dark-brown/black	Slight color change to darker	No noticeable change

- Part 3, Step 10: Groove in skin in air quickly turned brown to dark-brown. Groove in skin under water did not turn brown.
- Part 3, Step 11: Groove in skin taken from water into air turned brown to dark-brown.
- Part 3, Step 12: A piece from a slightly riper banana showed further darkening to black. A piece from a less ripe banana showed no noticeable change.

Tips

- Students may wish to have the rest of the banana as a color comparison to the original. If it is difficult for students to tell if a groove has changed color, they could do a new groove next to it and compare immediately.
- Longer bananas could potentially be split between two students/groups. Instead of making the design at the bottom in Part 1, Step 1, the second group would make the design at the top.
- If the banana is less ripe, it may take more than one drag with the toothpick to break through the surface of the outer peel.
- Instructors could purchase greener bananas several days before the experiment and let them ripen beforehand.

Teacher Notes (continued)

- Round toothpicks are used because they have a sharper tip than flat toothpicks. Both are typically available at grocery stores.

Background Information

The cells of bananas contain phenolic compounds and enzymes (polyphenol oxidases) that catalyzes oxidation reactions of these compounds. Phenolic compounds contain hydroxylated aromatic rings. In a plant cell, the phenolic compounds are compartmentalized separately from the enzymes. However, if the cell is damaged, the separation can break down so they can come together. For example, this can occur if the bananas are affected by being handled roughly or dropped, by pest or pathogen attack, or by deterioration of the cells through age. Oxygen is also needed for the reaction to occur.

The process does have a purpose: "This system is one of the plant's chemical defenses: when insects or microbes damage its cells, the plant releases reactive phenolics that attack the invaders' own enzymes and membranes" (McGee, H. *On Food and Cooking: The Science and Lore of the Kitchen*, Scribner, New York, 2004, p 269). Other foods that show similar enzymatic browning are avocados, apples, apricots, mushrooms, pears, and lettuce.

Teachers could use the *Scientific American* video "Why Do Bananas Change Color?" as a brief summary. The video also mentions several other enzymes present in bananas.

Question 1
The video (2 min, 3 sec) "What Happens When Bananas Ripen?" gives a short summary of the chemistry of the process.

Question 4b
A 2018 *Biosensors* journal article discusses the use of polyphenol oxidase biosensors.

Teacher Notes (continued)

Experiment Extension Ideas

Part 1, Step 2 and Part 2, Step 5
Students could take digital video of the banana pieces as they brown to collect visual color data to refer to later. They could then use the video and its timing to graph observations of color versus time, with time in seconds on the x-axis, and a visual scale on the y-axis, with terms such as light yellow, light brown, dark brown, black. This could provide very rough visual estimates of reaction rates.

Students could modify the experimental conditions (e.g., pH, temperature) to compare how it affects the rate of browning. Depending on results seen, students could discuss how this relates to the use of directed evolution to create enzymes that work at different rates or in different conditions.

Question 3
Students could make a more in-depth study of melanin. They may already be familiar with its presence in human skin and its relation to tanning.

- The podcast (with transcript) Melanin from *Chemistry World* offers an accessible introduction to the family of melanin pigments and where you'll find them.
- A more advanced option is the review article "Melanins: Skin Pigments and Much More—Types, Structural Models, Biological Functions, and Formation Routes."

Question 4c
Teachers could expand this question to prompt students to consider how they would "challenge" the polyphenol oxidase enzyme to evolve it. What would they change to adapt it to a specific need or environment? How could they set up a directed evolution reaction?

Students could also read the description of an apple on the market that has had its browning process modified and discuss how directed evolution could have contributed.

Chemistry Shorts™ is a film series that communicates the breadth and depth of chemistry's impact on humankind in an approachable manner, sponsored by the Camille and Henry Dreyfus Foundation. These films will celebrate the science and the people who share a passion for the vital role chemistry plays in the biggest issues, including human health, renewable energy, the nature of life, sustainability, new materials, and climate change. Each film incorporates a lesson plan that offers ideas for ways they may be incorporated into the classroom. We welcome your feedback at: chemistryshorts.org.

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