Penn State RET in Interdisciplinary Materials

Teacher's Preparatory Guide

Salad Motors

Purpose: This experiment is designed to introduce secondary-school students to micro and nano motors using a macro-scale approach.

Objectives:

- Build macro motors using simple, easily accessible materials.
- Explore the action that propels a macro motor.
- Collect and analyze data on different "salad" macro motors.
- Compare the limitations of the macro world with those of the micro and nano world.
- Review interdisciplinary concepts.

Time: 1–2 class periods of ~45 minutes each.

Level: High School (Grades 9–12) (Can be used at any grade level from K–12 with modifications)

Next Generation Science Standards: (Grades 9–12)

HS-PS1-5 Apply scientific principles and evidence to provide an explanation about the effect of changing the concentration of the reacting particles on the rate at which a reaction occurs.
HS-PS1-7 Use mathematical representations to support claims.
HS-PS2-6 Communicate scientific and technical information in multiple formats (orally, graphically, textually, and mathematically.
HS-PS1-5 Apply scientific principles and evidence to provide an explanation about the effects of changing temperature or concentration of the reacting particles on the rate at which a reaction occurs.
HS-PS2-5 Apply scientific principles and evidence to provide an explanation of phenomena and solve design problems, taking into account possible unanticipated effects
HS-PS2.1 Newton's Second Law accurately predicts changes in the motion of macroscopic objects.

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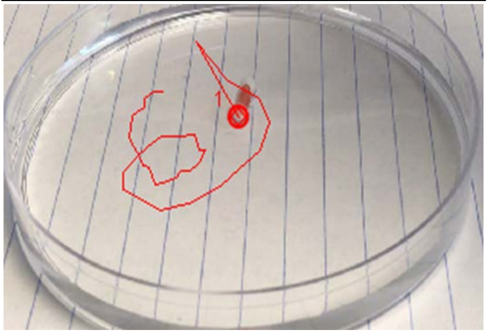
Pennsylvania Science Standards: (Grades 9–12).

3.2.C.A4: Predict how combinations of substances can result in physical and chemical changes.
3.2.C.A1: Differentiate between physical properties and chemical properties.
3.2.10.B1: Analyze the relationships among the net forces acting on a body, and the resulting acceleration, using Newton's Second Law of Motion.
3.1.B.A2: Explain the importance of enzymes as catalysts in cell reactions. Identify how factors such as pH and temperature might affect enzyme function.
3.1.C.A1: Explain the chemistry of metabolism.
3.4.12.C3: Apply the concept that technological problems require a multi-disciplinary approach.

Teacher Background

Salad motor pathway in a petri dish.



Micro and nano motors are the focus of cutting-edge research. These tiny motors use the chemicals in their environment as fuel and convert the energy released from the breakdown of the fuel to mechanical energy. The phenomena that affect objects at the micro and nano scale are difficult to visualize in a classroom. "Salad Motors" is an experiment that prepares students to meet the demands of current research and technology, using simple materials and promotes the understanding of interdisciplinary science concepts.

Hydrogen peroxide (H_2O_2), a toxic product of cell metabolism, was used as a fuel for underwater propulsion in Germany in 1934. H_2O_2 also has a long history of use in the aerospace industry. The enzyme catalase, which is found naturally in many fruits and vegetables, decomposes H_2O_2 into water and oxygen. This chemical reaction is exploited in this experiment to propel macro motors though the action of bubble propulsion. Reactions catalyzed by enzymes can be speeded up, slowed down, or stopped by changing the following factors: temperature, pH, concentration of reactants, and the presence of inhibitors.

(Catalase)

$2H_2O_2 \rightarrow O_2 + 2H_2O$ ΔH = -98.3 KJ/mol

Materials: (for one laboratory group)

- 6 *Plastic pipette tips (0.5 cm)*
- 1 Exacto® knife

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- 1 sheet of paper towel
- 1 plastic petri dish (90 mm in diameter)
- 1 pair of plastic tweezers
- 2 pieces each of produce (carrot, or potato, or cucumber, or red pepper with apple) 0.75 cm x 1cm x 1cm
- 1 cotton applicator
- 50 mL beaker
- 1 hot plate
- 20 mL of paraffin wax
- 1 iPad with camera
- 50 mL vial of 3% H_2O_2
- 50 mL vial of 10% H_2O_2
- 50 mL vial of 30% H_2O_2
- ice in Styrofoam container with lid
- 25 mL graduated cylinder
- neoprene gloves
- 1-metric ruler


Demonstration of Catalase Activity

Advance Preparation:

Cut pipette tips to 0.5 cm in length. Prepare 6 pipette tips for each group. (If working with younger children, use plastic straws and increase the size to 1 cm.) Buy fresh produce (1 apple, 1 cucumber, 1 carrot, 1 red pepper, 1 potato). You can try other vegetables that are high in catalase. This produce should be enough for several lab groups. Thinly slice the produce so that each group can have a piece with the dimensions 0.75 cm x 1cm x 1cm. (If using straws, make the dimensions thicker to fit easily into the straw.) Make sure the produce is cold and does not dry out. Use new bottles of 30% H_2O_2 to prepare the 10% and 3% dilutions on the day of the experiment. Prepare the 10% H_2O_2 for one group by adding 33.33 mL of deionized water or phosphate buffer (pH 7.2) to 16.67 mL of 30% H_2O_2 solution. Prepare the 3% H_2O_2 for one group by adding 45 mL of deionized water or phosphate buffer (pH 7.2) to 5 mL of 30% H_2O_2 solution. Store the solutions in labelled plastic vials with ice before and during the experiment. Label a 2 L beaker for H_2O_2 waste. At the end of the experiment, dilute the beaker with twice the quantity of water, and pour it down the drain.

For the demonstration before students perform the experiment, use a mortar and pestle to mash some carrot, cucumber, apple, red pepper, and potato separately. Mass out 600 g of each mashed vegetable and place into separate 10 cm-tall test tubes or 10 mL graduated cylinders. Add 100 µL of a dish detergent into each test tube. During the demonstration, you will add 1 mL of 30% H_2O_2 into each test tube and gently agitate each test tube after adding H_2O_2.

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Safety Information:

Wear gloves to protect your hands from the oxidizing power of H_2O_2. Wear safety goggles. Use caution when cutting produce pieces with the Exacto® knife. Dispose motors and produce into the trash cans. Discard used H_2O_2 in the beakers of labelled "H_2O_2 Waste." Keep metal objects away from the H_2O_2 (H_2O_2reacts with metals).

Teaching Strategies:

Each laboratory group should contain 2–3 students. Students should read the *Scientific American* article, listed in the resource section, before the experiment, or they should have an overview on micro and nano motors before they perform this experiment. Ask students to research online for the catalase levels of the different vegetables. Students should review the following terms and concepts before the lesson: enzyme, substrate, chemical reaction, viscosity, drag, nanometer, Brownian motion, inertia, Newton's Three Laws of Motion.

Resources:

How to Build Nanotech Motors: *Scientific American*. <http://www.sciam.com/article.cfm?id=how-to-build-nanotech-motors&print=true>

Catalase– An Extraordinary Enzyme. <http://www.catalase.com/cataext.htm>

Self-Assembly of Nanorod Motors into Geometrically Regular Multimers and Their Propulsion by Ultrasound. <http://pubs.acs.org/doi/abs/10.1021/nn5039614>

Self-propelled chemically-powered plant-tissue biomotors. <https://www.researchgate.net/publication/249320386_Self-propelled_chemically-powered_plant-tissue_biomotors>

Hydrogen Peroxide Propulsion Guide. <https://www.diyspaceexploration.com/hydrogen-peroxide-propulsion-guide/>

Video Analysis and Modeling Tool. <http://physlets.org/tracker/>

Instructional Procedure:

Warm-Up *(~10 minutes)***:** Assign terms or concepts to review by group, 2–3 terms per group. Call on groups to share their meanings with the whole class after a couple of minutes of collaboration.

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Review Terms:

Enzyme: *Macromolecular biological catalysts that help accelerate chemical reactions.*

Substrate: *The substance on which an enzyme acts.*

Decomposition: *A chemical reaction in which a reactant breaks down into its products.*

Exothermic reaction: *A chemical reaction that is accompanied by an overall release of energy.*

Viscosity: *The resistance to flow..*

Surface Tension: *The stretched surface of a liquid where the liquid occupies the least surface area possible.*

Drag: *A force that acts opposite to the direction of motion of an object.*

Nanometer: *A unit of measurement (nm) where 1nm = 10^{-9} m.*

Brownian motion: *Random motion of particles when suspended in a fluid.*

Newton's Three Laws of Motion:

1^{st} Law: An object in motion remains in motion, and an object at rest remains at rest unless acted on by an external unbalanced force.

2^{nd} Law: When a net force acts upon an object, the object moves in the direction of that net force.

3^{rd} Law: For every action, there is an equal but opposite reaction.

Review Safety Information *(~2 minutes)*

Demonstration: *(~ 5 minutes)*

Perform the demonstration for students after you review the chemical reaction used in this experiment. Explain that the vegetables are natural sources of catalase and that the demonstration estimates the amount of catalase present in each vegetable.

Question:
If all the motors are fueled by the reaction of catalase on the H_2O_2, rank the motors by speed with the fastest motor being first. What is the basis of your ranking?
Answers will vary. Students should base their prediction on the activity of catalase they observed in the demonstration.

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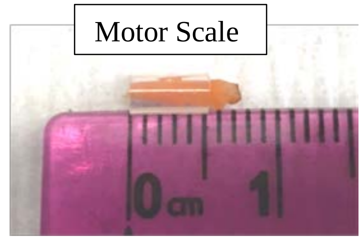
Procedure: *(~40 minutes)*



- Spread the paper towel on the laboratory station.
- Heat the wax in the 50 mL beaker on the hot plate.
- Choose a vegetable piece (carrot, potato, cucumber, or red pepper) and a piece of apple.
- While the wax is melting, use the Exacto® knife to cut a thin sliver of the vegetable piece and "load" a plastic pipette tip with the vegetable so that a tiny part of it protrudes out of the plastic piece. Look at the figure to the right. The motor should now be closer to 0.75 cm in length.
- To make the motor asymmetrical, seal the open end of the motor with a small amount of wax using the tweezers to hold the motor in one hand and the cotton applicator, dipped in wax, to seal the open end of the motor with the other hand. Gently blow on the hot wax to cool the wax seal.
- Prepare 6 motors (3 with vegetable pieces and 3 with apple pieces) using the technique above.
- In the Styrofoam containers, you have 3 labelled vials with H_2O_2 (3%, 10%, and 30%). Pour 25 mL of 30% H_2O_2 into the petri dish provided. Turn on the iPad camera, and choose the video option. Place the iPad in front of the petri dish so that the whole petri dish fills the view of the camera. Do not move the petri dish or the camera.
- Clean up the work station.
- Mass a motor, and place the vegetable motor in the petri dish of H_2O_2, and record the motion of the motor for 2 minutes.
- Repeat the procedure above for all the motors you made.
- Record your observations. Load all 6 videos onto a computer.
- Go online and open the Video Analysis and Modeling Tool. << http://physlets.org/tracker/>>
- Drag and drop one of the videos of a motor into the program. Set the axes (move them to frame the petri dish) and the calibration bar (90 mm for the width of the petri dish). Track the motor's movements by skipping every 100 frames.
- Once you have the "x" and "y" coordinates for each movement, use the distance formula to calculate speed of each displacement. Use a program like Microsoft's Excel or Apple's Numbers to calculate speed. Average the speeds for that motor.
- Repeat the procedure above for all the motors you made.

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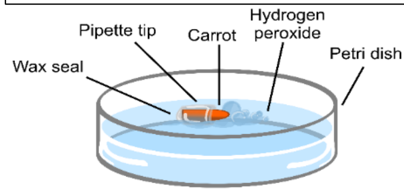
Experimental Set-Up



Data Tables and Calculations: *(~40 minutes)*

Calculate speed (v) = total distance (d) /total time (t)

Distance formula d = $\sqrt{(\Delta x)^2 + (\Delta y)}^2$

Group Data

H_2O_2	Apple Motor #1	Speed of Motor #1 (mm/s)	Mass # 1 (mg)	________ Motor #2	Speed of Motor #2 (mm/s)	Mass #2 (mg)
3%						
10%						
30%						

Class Speed Data

H_2O_2	*Apple Motor Speed (mm/s)*	*Carrot Motor Speed (mm/s)*	*Cucumber Motor Speed (mm/s)*	*Potato Motor Speed (mm/s)*	*Red Pepper Motor Speed (mm/s)*
3%					
10%					
30%					

Students can calculate kinetic energy (KE) = ½ mv^2. Units should be in pico Joules (pJ).

Class Kinetic Energy Data

H_2O_2	*Apple Motor KE (pJ)*	*Carrot Motor KE (pJ)*	*Cucumber Motor KE (pJ)*	*Potato Motor KE (pJ)*	*Red Pepper Motor KE (pJ)*
3%					
10%					
30%					

Results:

- *Class data may be placed on a common table on the whiteboard so that students can make comparisons. If more than one group worked on a particular motor, then their data can be averaged to find the speed of that type of motor.*

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- *Responses may vary; apple motors have the lowest amount of catalase and will be consistently the slowest. Carrot motors in 10% H_2O_2 display the highest overall speeds.*
- *Data from the kinetic-energy calculations should, in general, be consistent with the speed data.*
- *Speed and kinetic-energy calculations may be done on a program like Microsoft's Excel.*
- *Students may display class data in a graph. Bar graphs seem to be the best.*
- *Students should relate motor speeds to the amount of catalase in the vegetable.*
- *Students should notice the starch trail which appears to slow down the motor.*
- *Discuss how their predictions compared with the class data.*

Closing Questions: *(Assign as Homework)*

1. Which motor seemed to be the overall champion and what percent of H_2O_2 fuel did it run on?
   The carrot motor appears to have the highest speed in 10% hydrogen peroxide overall.

2. Comment on the activity of the apple motor. What role did the apple motor play in this activity?
   The apple motor was the slowest motor overall in all percentages of H_2O_2. This motor serves as the control motor. Most of its motion appears to be related to Brownian motion. It probably has the lowest concentration of catalase among the salad motors used in this experiment.

3. Is there a pattern in the data collected for the 3 motors in 3 percentages of fuel? Explain.
   No, correlation appears to exist between the type of motor and the percentage of fuel used. The apple motors were the slowest in all concentrations of hydrogen peroxide. The carrot motor works the best at 10% H_2O_2.

4. Name some common fuels. Identify the fuel that the salad motors use.
   Examples: Hydrogen gas, petroleum-based fuels, uranium. The fuel that the salad motors use is H_2O_2.

5. Viscosity of the substrate changes as the fuel is used up. Explain.
   As the enzyme in the motor decomposes the substrate and the motor is propelled through the substrate, the viscosity of the substrate changes. The viscosity of H_2O_2 solution is greater than the viscosity of water that is formed as a result of the decomposition.

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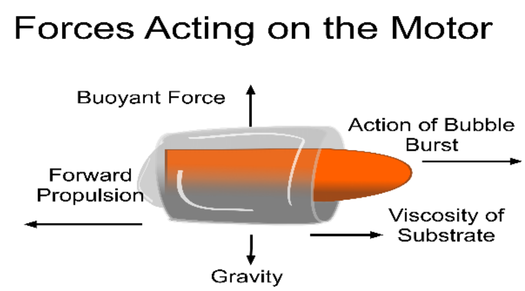
6. What evidence is available in this activity to demonstrate that energy is present in chemical bonds?
When H_2O_2 *decomposes, energy is released and temperature of the substrate mixture increases. The oxygen gas bubbles expand and burst; this action propels the motor forward (chemical energy converts to mechanical energy and thermal energy. The mechanical energy is then converted to kinetic energy.)*



7. Draw the forces acting on a motor as it propels over the surface of the substrate. Which is the strongest force working against the forward motion of the motor?
The force diagram is to the right. The viscosity of the substrate opposes the forward motion.

8. Explain the role that inertia plays on a macro motor vs the role that inertia plays on a micro or nano motor.
The motor has to overcome inertia before it begins to move on the surface of the substrate. In the case of the nano and micro motors, the mass of the motors is negligible; so, inertia is negligible.

9. Explain how Newton's Second Law of Motion may be used to explain the motion of the motor.
Newton's Second Law of Motion states that when a net force acts upon an object, the object moves in the direction of that net force. In this experiment, the net force is provided mostly by the burst of the bubble and the direction of this force is determined by the resultant vector of all the forces acting on the motor.

10. How can the enzyme in the decomposition reaction of H_2O_2 be denatured? How would denaturation of the enzyme affect a motor's activity?
The function of enzymes is affected by changes in temperature, pH, and concentration of reactants. Denaturation stops the motor from moving.

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