Teacher Preparatory Guide
Nanomotors

Overview: As scientists develop more complex and advanced nano devices, a variety of propulsion systems have been proposed for providing a means of moving these devices for the purpose of accomplishing exciting feats. Scientists have envisioned such innovations as nano-trolleys that deliver drugs to cancer cells as well as nano-scapels that perform delicate surgery without the need for creating an incision in the skin. In this activity, students will explore some of these proposed propulsion designs and will explore the factors that affect the performance of these systems. Students will conduct a hands-on propulsion experiment by building and testing centimeter-scale boats powered by (1) Isopropyl alcohol and (2) a catalytic platinum coating. With respect to the platinum boats, students will compare the centimeter-scale propulsion system with the similar-appearing (but distinctly different) mechanism that has been shown to drive nanowires made of platinum and gold. Finally, they will research other nanoscale propulsion systems that have been proposed by scientists around the world.

Purpose: This lesson is designed to engage students in hands-on experiments that explore nanoscale propulsion principles and guide students in recognizing and analyzing differences between macroscale and nanoscale propulsion systems.

Time required: Two 45 minute class periods or one 90 minute block period.

Level: High School Chemistry and Physics

Materials per class (of 6-8 student groups):

- Foam poster board (1/4" thick, standard poster dimensions)
- One fine painting brush (per student group)
- One Hobby Knife (per student group)
- One 6"x 6"x 2"deep Tupperware or comparable basin (per student group)
- One Small Glass vial (8-25 mL)
- Two micropipettes (per student group)
- Platinum (50%) on Carbon and Nafion resin
- Hydrogen Peroxide (6%) *(Note: 3% household type produces insufficient propulsion)*
- 25 mL Isopropyl Alcohol

Safety Information: Safety glasses should be worn at all times. If the **platinum on carbon power** is used, use special care as it is **extremely reactive**. The powder may ignite while being transferred into the Nafion. Keep powder away from open flames and sources of ignition. Nafion, if inhaled, is harmful to the respiratory and nervous systems as well as the kidney and liver. Use ventilation (fume hood if possible, otherwise open windows) and wear gloves. Avoid contact with eyes, skin, and clothing. If eye contact is made, flush eyes with large amounts of water for 15 minutes and seek medical attention. Wash thoroughly with soap and cool water if

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contact is made with skin. Use special care when using hobby knives. Hydrogen peroxide is corrosive to the skin and lungs if vapors are inhaled. Use caution and provide adequate ventilation (fume hoods, if possible).

Teacher Advance Preparation:

Where to buy supplies:

- Platinum (50%) on Carbon – Alfa Aesar, Product #43989 (http://www.alfa.com/)
- Nafion resin – Aldrich, Product #527084-25ML (http://www.sigmaaldrich.com/united-states.html)
- Hydrogen Peroxide (30%) – Aldrich, Product #216763-100ML

(Please Note: Total material cost for this activity is approximately $250.)

Preparing the Platinum Catalyst

The platinum-on-carbon powder can be very reactive and prone to igniting as it is being added to the Nafion. The teacher may wish to do this mixing in advance (or possibly as a demonstration in front of the class). Keep in mind that the paint will need to be stirred for about an hour prior to application.

Mixing the Platinum-on-Carbon powder and the Nafion:

1. Insert a magnetic stirring bar into the glass vial.
2. Use a pipette to dispense 1 mL of Nafion into the bottom of a glass vial.
3. Use a balance to measure 0.100g of the platinum-on-carbon powder into a plastic balance tray. Tap the powder into the glass vial containing the Nafion. **(Be alert for ignition of the powder as it is very reactive.)**
4. Tighten the cap on the vial and place it on a stirring place. Stir at 3500 rpm for 1 hour prior to applying.

If using the platinum foil and ribbon, you will simply be using scissors to cut the foil into pieces that correspond in size to the dimensions of the back of your boats. In this case, wait to cut the foil until you have cut out the boats.

Diluting the 30% Hydrogen Peroxide to 6%

In its commercial form, the hydrogen peroxide is concentrated at 30% in water. While this concentration will produce a very vigorous propulsion reaction, it is corrosive to the skin and lung if vapors are inhaled. Dilute to roughly 6% by mixing one part hydrogen peroxide with five parts water. You may want to make stronger dilutions to allow students to experiment with different concentrations (Part 1 B.4).

Preparing the Foam Boats

This activity was designed to use standard poster-size foam board (1/4" thick) as the material for the boats. Hobby knives or scissors may be used to cut out the boat pattern from the foam board. Depending on the level of the students in the class, teachers may wish to do this step in advance. Each team will need two boats. In one boat, a well and channel for dispensing isopropanol (IPA) will need to be created.

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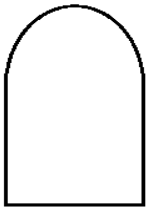
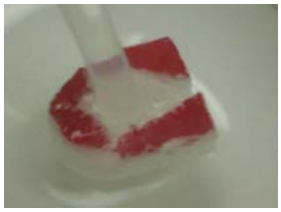
Boat Diagrams

Both boats will be cut to the same general pattern (shown in full-scale on the left below). Only one of the boats will need to have additional cutting to create a small well and channel for carrying and dispensing the IPA.



Boat Shape Pattern
(full-scale)



Well and Channel
(depth = 3-4 mm)
for IPA boat only

Teacher Resources You may wish to use these resources either as background or as a resource for students to use in their inquiry-based design.

Site	**Topics**
Behind the Scenes article *Nanoparticles Taught to Swim* www.livescience.com/technology/081107-bts-moving-nano.html	Nanowire Propulsion
Scientific American article *How to Build Nanotech Motors* http://www.scientificamerican.com/article.cfm?id=how-to-build-nanotech-motors	Nanowire Propulsion (Scientific American article)
Nanomotor Video www.SciAm.com/nanomotor	Video of Catalytic Propulsion of Nanowires
Popular Science article *A Photon-Powered Nanomotor Made Out of DNA* www.popsci.com/category/tags/nanomotors	Nanomotor Research

Journal articles

1. Mallouk, T., Sen, A., Powering Nanorobots. *Scientific American*. May 2009. pp 72-77.

2. Ismagilov, R., Schwartz, A., Bowden, N., Whitesides, G.M., Autonomous Movement and Self-Assembly. *Angew. Chem.*, 41, No. 4., 2002, 652-654.

Teaching Strategies This lab can be done individually or in groups of 2-3 students. It is better to keep the group size small so that each individual can propel his or her own boat.

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Part 1 – Instructional Procedure
Building Centimeter-Scale Boats Powered By Platinum Catalysis

Time (minutes)	Instructional Activity
15	Introduce the activity using the video found at www.SciAm.com/nanomotor. Have students brainstorm regarding possible applications of self-propelled nano devices. Have students compare the how and why phenomena such as Brownian motion and surface tension have difference effects on the macro and micro scales. Use this link to show Brownian motion: http://www.andrew.cmu.edu/user/dcprieve/Brownian%20motion%20of%20emulsion.avi or explore Brownian motion at: http://www.youtube.com/watch?v=KQgydF-fXvc
15	Distribute two foam boats to each team of students. One boat should have a well in it for the Isopropanol. Teams will now apply the Platinum-on-carbon "paint" to the other boat (with no well). a. Instruct students to use a pen, pencil, or marker to label their boats with their initials or team name. b. Set up a painting station so that students may share a common container of paint to reduce waste. c. Have students rotate through the painting station with no more than two or three groups painting at one time. d. Designate an area or location where the students may allow the paint on their boats to dry until the next class day. e. Have students return brushes to location specified by the teacher.
10	Have students complete the "Purpose", "Questions", and "Key Terms" section of the student worksheet.
5	Review and reflect on the videos viewed at the beginning of class. Discuss the completed sections of the student worksheet and preview the propulsion tests that will be conducted tomorrow.

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Part 2 – Instructional Procedure
Observations of Nano Propulsion

Time (minutes)	Instructional Activity
5	Have students retrieve the boats they labeled with their names during the previous class period. To begin, they will be completing the hydrogen peroxide and platinum *Student Worksheet* that they began in the previous class period. They will only need their boat that was painted with platinum for the beginning of the lesson.
10	Have the students complete their Student Worksheet as they observe the propulsion of their peroxide-platinum boats. a. Have the students use a micropipette to dispense the 6% peroxide solution into a shallow (< 1 cm) layer in a 6"x 6"x 2"deep Tupperware or comparable basin. b. The students should gently place their boat with the platinum layer on the air-water interface of the solution and measure the speed of its motion using a ruler and stopwatch. They may need to briefly submerge the platinum coating to facilitate the reaction. c. Instruct students to record observations of the platinum catalysis process that produces the motion. d. Optional: Allow the students to experiment with different concentrations of peroxide (by using a pipette to decrease the concentration by adding water) to determine any affect on the boat's speed. You may wish to demonstrate a higher concentration from your teacher station. e. To allow time for the IPA boat test, instruct the students to complete Question 5 on the *Student Worksheet* after all of the testing has been completed.
5	Have the students rinse with water the platinum surface of their first boat and set it aside. Have them pour their hydrogen peroxide solutions down the drain as they run the water. The basins will now be reused so they will need to be rinsed thoroughly with water. Have the students place enough water in the basin to provide a depth of about 1 cm.
10	Have students complete the *Purpose*, *Questions*, and *Key Terms* section of the *IPA Boat Student Worksheet*.
10	Have the students complete their *IPA Boat Student Worksheet* as they observe the propulsion of their IPA-powered boats. a. The students should gently place their boat with well on the surface of the water. b. Have the students use a micropipette to dispense one or two drops of IPA into the well on their boat. c. Instruct students to complete their *Student Worksheet* and record observations of the motion that results. d. Have students return materials to their designated locations.
5	Review and reflect on students observations recorded on the *Student Worksheet*.

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Name_____ Date_____ Class_____

Part 1: Platinum-Catalyzed Propulsion of Foam Boats
Student Worksheet (*with answers*)

Introduction
As scientists develop more complex and advanced nano devices, a variety of propulsion systems have been proposed for providing a means of moving these devices for the purpose of accomplishing exciting feats. Scientists have envisioned such innovations as nano-trolleys that deliver drugs to cancer cells as well as nano-scapels that perform delicate surgery without the need for creating an incision in the skin. In this activity, we will explore one of these proposed propulsion designs and will explore some factors that affect the performance of the system.

Purpose
1. To build a vessel powered by hydrogen peroxide catalyzed by platinum.
2. To observe the motion and processes involved in a macro-scale platinum catalytic engine.

Question(s)
1. In what way(s) can a catalytic reaction provide a means of propulsion?
2. How might a catalytic propulsion system work differently on the nanoscale as compared to the macroscale?

Hypothesis Develop a hypothesis to answer one or both of the questions listed above.
As an illustration of Newton's 3rd Law, the catalytic reaction that produces oxygen bubbles in a solution of hydrogen peroxide will provide a forward force on the Styrofoam boats.

Key Terms

Source: *Dictionary.com Unabridged (v 1.1)*. Retrieved July 23, 2009, from Dictionary.com website: http://dictionary.reference.com/browse/catalysis

Brownian Motion: *the irregular motion of small particles suspended in a liquid or a gas, caused by the bombardment of the particles by molecules of the medium: first observed by Robert Brown in 1827.*

Catalysis: *the causing or accelerating of a chemical change by the addition of a catalyst.*

Materials per class (of 6-8 student groups)
- Foam poster board
- One fine painting brush (per student group)
- One Hobby Knife (per student group)
- One 6"x 6"x 2"deep Tupperware or comparable basin (per student group)
- One Small Glass vial (8-25 mL)
- One micropipettes (per student group)
- Platinum Ribbon/Foil or *Platinum (50%) on Carbon* and *Nafion resin*
- Hydrogen Peroxide (6%) *(Note: 3% household type produces insufficient propulsion)*

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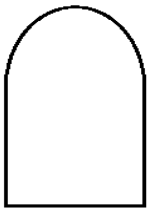
Procedure

A. Preparing the Platinum-Peroxide Boat

1. Assembling the Boats
    a) Cut the boat shape shown below out of foam poster board.



2. Apply the platinum layer to the back of the boat. Use a fine-tipped artists' brush to carefully spread a layer of platinum across the entire back side of the boat. Allow to dry for at least 2 hours.

B. Testing the Boats

1) Use a micropipette or beakers to dispense the 6% hydrogen peroxide solution in a shallow (< 1 cm) layer in a 6"x 6"x 2"deep Tupperware or comparable basin.

2) Gently place the boat on the air-water interface of the solution. Initially, push the back side of the boat downward so that the platinum surface becomes entirely submerged in the solution. Observe and record evidence that the catalytic reaction is taking place.

Bubbles form on the surface of the platinum. The bubbles are produced by the oxygen that is produced as the hydrogen peroxide (H_2O_2) is catalyzed by the platinum.

3) Observe and describe the motion that is produced as a result of the reaction. If possible, measure and record the speed of the boat as it moves through the peroxide solution.

The motion will be generally straight forward, subject to the boundaries of the container and the general shape of the boat. Expect speeds of 1-3 cm/s.

4) Experiment with different concentrations of peroxide (if available) to determine any affect on boat speed or the production of bubbles. Describe any effects of concentration on the motion of the boat.

Higher concentrations will produce faster rates of speed. At lower rates, bubble action will become insufficient to provide propulsion.

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5) Review the article and video found at the links below. Summarize how hydrogen peroxide and platinum propulsion functions differently on the nanoscale.
www.SciAm.com/nanomotor
http://www.scientificamerican.com/article.cfm?id=how-to-build-nanotech-motors

On the nanoscale, the size of the devices is too small to be driven by bubble propulsion. Instead, electrostatic action-reaction forces take over as ions from the catalysis reaction travel from one end of the nanomotor to the other, pulling polar water molecules with them. In reaction to this force, the nanomotors are propelled toward the platinum end.

Name_____ Date_____ Class_____

Part 2: Isopropanol (IPA) Propulsion
Student Worksheet (*with answers*)

Introduction
Surface tension is a property of liquids that produces an inward force along the surface of the liquid. Fluids with high surface tensions "bead" as water does when it is poured over a newly waxed car. Isopropanol, in contrast, possesses a low surface tension. This lack of inward force means that when an object is bordered on one or more sides by isopropanol, the isopropanol will exert a greater force against the object than a liquid with a higher surface tension. In this activity, we will attempt to manipulate this property to provide a propulsion system for a centimeter-scale boat.

Purpose
1. To build a vessel powered by the differing surface tensions of water and isopropanol.
2. To analyze the effect of scale on usefulness of surface tension as a source of propulsion.

Question(s)
1. How does surface tension affect the way in which a liquid exerts forces on surrounding objects?
2. Why do changes in surface tension affect motion on some scales but not others?

Hypothesis Develop a hypothesis to answer one or both of the questions listed above.
Liquids with less surface tension, which is an inward force, exert larger forces on surrounding objects.

Key Terms

Surface Tension: *The force exerted along the surface of a fluid that causes it to "bead up" and form into drops. Water has high surface tension and beads up easily; alcohol has low surface tension and does not often show droplets.*

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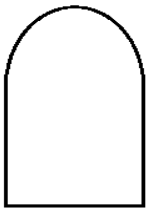
Materials (per class unless otherwise indicated)

- Foam poster board (1/4" thick, standard poster board dimensions)
- Hobby Knife
- 8x10 baking pan (1 per group)
- Micropipette (1 per group)
- Isopropyl Alcohol (2 mL per group)

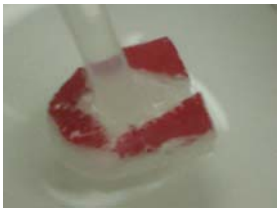
Procedure

A. Preparing the Isopropanol (IPA) Boat
**Your teacher may complete this step due to time and safety considerations.*

1. Cut the boat shape shown below out of foam poster board using scissors or a hobby knife.



2. Use a hobby knife to create a well and channel in the boat for carrying and dispensing isopropanol. The well should be approximately 3-4 mm deep and shaped as indicated in the figures below.



B. Testing the Boats

1. Set up your IPA boat experiment as follows:
   a. Fill your basin with approximately 1 cm of water.
   b. Gently place your boat on the surface of the water.
   c. Using a micropipette, dispense one or two drops of IPA into the well on your boat.
   d. Complete the questions below and record observations of the motion that is produced as the IPA exits the channel at the rear of the boat.
   e. Return your materials to their designated locations when your experiment is completed.
2. Observe any visible evidence that a propulsion process is taking place.

Because water and IPA are similar in appearance, it can be difficult to see anything happening that would cause the boat to be propelled forward. There is no dramatic reaction as was the cause with the previous boat.

3. Observe and describe the motion that is produced as a result of the reaction. If possible, measure and record the speed of the boat as it moves through the peroxide solution.

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The motion will be generally straight forward, subject to the boundaries of the container and the general shape of the boat. Expect speeds of 2-4 cm/s.

Final Reflection Questions (*with answers*)

1. What do surface tension and Brownian motion have a larger impact on small-scale devices than they do on macro-scale objects?

   On the macro-scale, the inertia of massive objects and the magnitude of applied forces render nano-scale forces insignificant.

2. Explain how the different surface tensions of water and isopropanol can be utilized to create a propulsion system.

   Surface tension is the inward force of along a liquid's surface. If a liquid has less surface tension, there is a larger outward force exerted along the surface of the liquid. Therefore, when isopropanol (with a lower surface tension) is released behind a boat, it exerts a larger force on the rear of the boat than the water is exerting on the front of the boat. As a result, the boat is propelled forward.

3. Brainstorm with your partner and develop a concept for a nano-scale propulsion system based on a force or phenomena that is insignificant on the macroscale.

   Answers may vary. An example would be the energy of photons being used to move nanoscale objects.

Assessment

Assessments *for* Learning

Following each activity, allow time for discussion involving the questions and observations. In addition to sharing responses to the activity questions, the students should be encouraged to explore additional innovative ideas for providing propulsion on a nanoscale. Guide students in brainstorming how nanopropulsion could be used to facilitate advancements in areas such as medicine.

Assessments *of* Learning

Description	What is Assessed	Feedback
The students will complete the activity by constructing and testing centimeter-scale boats powered by (1) platinum-catalyzed hydrogen peroxide and (2) isopropanol.	Questions and procedures within the lesson provide a means of assessing the students' understanding of the key concepts and core questions. Students should be	Students receive a score according to the completeness and accuracy of their answers, and the organization of their notes. They also receive comments when the wrong

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Students will use their previous knowledge involving basic fluid properties and will acquire and develop an understanding of concepts such as Brownian motion, catalysis, and surface tension.	expected to explain why the significance of different propulsion forces is affected by the scale of the object that is in motion.	answer or explanation is provided which both challenges the misconception, and provides further explanation of the correct concept.

National Science Content Standards: Grades 9-12

A. Science as Inquiry

- Identify questions that can be answered through scientific investigations
- Design and conduct a scientific investigation
- Use appropriate tools and techniques to gather, analyze, and interpret data
- Develop descriptions, explanations, predictions, and models using evidence
- Think critically and logically to make the relationships between evidence and explanations
- Communicate scientific procedures and explanations

B. Physical Science – Structure and Property of Matter section

- Structure and properties of matter
- Chemical reactions
- Interactions of energy and matter

E. Science and Technology – Abilities of Technological Design section

- Identify appropriate problems for technological design
- Design a solution or product
- Implement a proposed design
- Evaluate completed technological designs or products
- Communicate the process of technological design

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