CNS Institute for Physics Teachers

Title:	**Vortex Rings**
Version:	July 2005
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Appropriate Level:	Grades 9-12
Abstract:	This experiment seeks to sharpen students' ability to observe, document and draw conclusions from a complex and visually appealing phenomenon. The elements of setting up controls in an experiment are emphasized. The intent is to shape the student's ability to design an experiment and to study and understand chosen aspects of a real-world phenomenon. The basic procedure involves dropping dye into water, which in many instances results in the formation of a vortex ring. Instability in the ring builds and the ring breaks into smaller drops which form a new set of rings. This process may repeat itself several times to create a cascade of rings. Vortex motion is widespread in the air and water that surround us, and this experiment makes it visible.
Time Required:	Two 45-minute periods, minimum
NY Standards Met:	M1.1 Use algebraic and geometric representations to describe and compare data. M2.1 Use deductive reasoning to construct and evaluate conjectures and arguments S2.1 Devise ways of making observations to test proposed explanations S3.4 Based on the results of the test and through public discussion, revise the explanation and contemplate additional research. 5.1i Construct and interpret graphs of position, velocity, or acceleration vs. time. 5.1ii Determine and interpret slopes of graphs and areas of motion graphs. 5.1d An object in linear motion may travel with a constant velocity or with acceleration.
Special Notes:	**Vortex Rings** is a kit available from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/.

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Objectives:

- Students will use scientific inquiry to pose questions and arrive at answers while observing a simple natural phenomenon.
- Students may be able to analyze observations in mathematical or graphical form.
- Students will use deductive and inductive reasoning in analyzing patterns and relationships of observed phenomena.
- Students will design a lab procedure that can enable them to study an aspect of the observed phenomenon.

Class Time Required:
Two 45-minute periods, minimum

Teacher Preparation Time Required:
30 minutes

Material Needed:

- tall clear containers (preferably square)
- hot/cold water
- thermometer
- food dye
- small container for dye
- ruler
- dye dropper
- stopwatch
- plate with hole
- dry erase marker
- paper towels/sponge
- ice
- salt
- practice container
- Video camera and TV (optional)

Assumed Prior Knowledge of Students:
Students need little background information for the lab. For an advanced approach, the teacher may introduce notations of density, viscosity, surface tension, miscibility, diffusion and convection prior to the experiment.

Background Information for Teachers:
This exercise has proven to be very engaging to anyone who tries it. It can be as simple or as complex as the teacher desires. This lab is designed to teach students the steps of the scientific inquiry process. It can also be modified and used to teach students the concepts of displacement and velocity.

Students observe vortex rings that occur when a drop of dye is released into a liquid. Initially, a single vortex ring forms; after traveling downward a certain distance, instabilities cause the primary ring to break into a "cascade" of smaller rings. The individual smaller rings then travel until they too become unstable and break into individual mini cascades. The cascade process can happen up to four times. Based on their observations of the vortex rings, students design and carry out an experiment to determine the effect of changing one variable on some chosen aspect of the phenomena observed.

Advanced investigations that take into consideration introductory concepts of fluid mechanics can also be done. In general, diffusion, convection, density, viscosity, and interfacial tension all play a role in vortex ring formation, motion and stability. A more advanced discussion may include concepts of cascades, stability of rings and the role of vortex motion in fluid mixing. See reference for more information.

Possible Answers to Questions:

The following is a sample answer for questions 1 – 6. Student answers will vary.

Experimental Design

1. List at least six items that you can measure when you drop the dye in the water. *water temperature, dye color, size of drop, height of drop above water, angle at which drop is placed in water, distance drop falls to first cascade*

2. What one item are you going to vary in this experiment? This is known as the "independent variable." *dye color*

3. What one item are you going to measure in this lab? This is known as the "dependent variable." *distance to first cascade*

4. List the remaining items from Question 1 that do not include the independent or dependent variable. These items must not be varied and are called the "constants" or "controls." (If they do change, it is very difficult to determine the effect of the independent variable on the dependent variable.) *water temperature, size of drop, height of drop above water, angle drop is placed in water*

5. Write a statement that describes what you think will happen to your dependent variable when you change your independent variable. This is known as the hypothesis. *When the color of dye is changed the distance to the first cascade will remain the same.*

6. Write an experimental procedure based on your hypothesis. Be sure to include controls, the independent and dependent variables along with safety concerns.
   a. *Fill each container with water to one centimeter below the top of the container. Let set.*
   b. *Pour dye into small container. Fill syringe with dye.*
   c. *Put plate and syringe at the top of the container.*

d. *Release drop at surface of water.*
e. *Mark the level of the first cascade.*
f. *Repeat steps (c) through (e) until there is too much dye in the container to see.*
g. *Repeat steps (b) through (f) for the other three containers. Use a different color of dye for each container.*
h. *Safety concern: Don't squirt anyone with dye.*

Data:

Color	Trial 1 Distance (cm)	Trial 2 Distance (cm)	Trial 3 Distance (cm)	Trial 4 Distance (cm)	Ave. Distance (cm)
Green	29	24	25	17	24
Red	16	23	24	29	23
Yellow	15	21	28	17	20
Blue	21	22	25	27	24

Conclusions/ Discussions

1. What in your data leads you to believe that your hypothesis is try or false? *The average distances were similar, from 20 to 24 cm, supporting the hypothesis that distance to the first cascade is not affected by dye color. Also, the variability between trials with the same color dye was greater than the variability between the dyes.*

2. Did you come across anything in the lab that you felt affected the outcome of the lab? If so, what were they and did they significantly affect the outcome of the lab? *Placing the thermometer in the container may have stirred up the water. Most of the measurements seem close to the first trial except for the red one. The numbers are closer on the last color (blue). That's the one with which we had the most practice. In each of the other ones, one or two numbers are different.*

3. How could you redesign you lab to get better data? *For the thermometer problem we could slide the thermometer in slower or get more thermometers and have one for each container. To get numbers that are closer we could practice more and then take more trials for each color by using two containers of water for each color.*

4. Based on your data and general observations, what could you further study? *We could time how fast the first cascade forms for each color.*

5. Using your answer to number 4, list the:
   a. *independent variable color*
   b. *dependent variable time*
   c. *controls water temperature, size of drop, height of drop above water, angle at which drop is placed in water, distance drop falls to first cascade*

   d. *hypothesis When a different color of dye is put into the water red will for a cascade first, then green, then yellow, then blue.*

6. Write an experimental procedure based on your answer to number 5.
   a. *Fill 8 containers with water to one centimeter below the top of the container. Let set.*
   b. *Pour dye into small container. Fill syringe with dye.*
   c. *Put plate and syringe at the top of the container.*
   d. *Release drop at surface of water and start a stopwatch.*
   e. *When the first cascade forms stop the stopwatch. Record data.*
   f. *Repeat steps (c) through (e) three to four times in that container.*
   g. *Repeat steps (c) through (e) in another container using the same dye color.*
   h. *Repeat steps (b) through (f) for the other dye colors. Use two water containers to make measurements for each dye color.*

   Safety concern: Don't squirt anyone with dye. Clean up any dye right after it is spilt.

7. Where do you see vortex motion in the real world? *smoke rings, tornadoes, Great Red Spot, eddy currents in streams, air currents behind jet wings*

   How are they like the vortex rings seen? *circular motion, temporary*

   How are they different from the rings seen? *no cascading, less matter diffused*

Tips for Teachers:

- The biggest limiting factor for the teacher is that the water has to be completely still before the lab is performed. The teacher must put the water in the container at least an hour before the lab.
- The lab may be introduced several different ways:
  - The teacher may start with a demonstration of the apparatus and then let students make observations at a lab station.
  - The teacher may present the apparatus and then let the students make observations.
  - The teacher may set up several different lab stations and guide the students to make observations at each.
- Measurable variables include but are not limited to the following:
  - release height of drop above water
  - number of cascades formed
  - vertical position of vortex ring
  - distance before ring breaks into a cascade of smaller rings

    - horizontal position of vortex ring
    - ring diameter
    - release distance from container wall
    - velocity of vortex ring (measure position as function of time)
    - temperature of the dye or water
    - size of the drop
    - dye color and mixing of different colors
    - different concentrations of solutes in the water
    - density of dye
- The number of containers of water per lab group should equal the number of variations being measured in order to have the water fully "settled." Students can do 3 – 5 trials per container by moving the location of the syringe.
- The plate with a hole for the syringe is both for bracing the syringe and for placing the dye drop at various locations in the container. If rested on a ring clamp attached to a ring stand, the height of the plate can be varied.
- Generally, the best rings form by having the dye drops just touch the water surface. If the drop is released too high (>8 cm or so), there is significant dispersion and a slower moving primary ring.
- One method of measuring the velocity of a vortex ring is to mark the location of the vortex ring at regular time intervals. Student A is assigned the task of dropping the dye into the water. Student B uses a stopwatch to count off regular time intervals. Student C watches the path of the vortex ring and marks the Plexiglas with a dry erase marker at the level of the ring when each time interval is called. When a ring cascades into a set of smaller rings, the student randomly picks one of them to follow.
- Measuring the average velocity of each cascade is possible with four students working as a team. Student A is assigned the task of dropping the dye into the water. Student B times the event with a stopwatch, starting at the moment the drop hits the water. When the first cascade occurs, student C marks the level of one (randomly picked) cascade and student B hits the lap time button on the stopwatch. Student D records the time. At each succeeding cascade, student B hits the lap time button twice so that the student D can record each time of a cascade. This method needs teamwork! Each group should practice dropping dye several times before actually taking measurements.
- Successful experiments have been done measuring velocity as a function of dye color, drop height and water temperature.
- Larger drops usually produce four cascades. Smaller drops only produce two or three. Using scissors, drop size may be changed by cutting the nozzle of the syringe. Make sure the edge of the nozzle made by the cut is even.
- The longest-lived primary ring is seen at 40-50 C. At higher water temperatures, natural convection in the container distorts the ring cascade. At lower temperatures, primary ring travels a shorter distance before splitting, so more cascade steps may be seen. Subrings tend to rotate around the primary ring in warm water.

- The range for changing dye density is very small as it will start to dissipate when diluted even a small amount. It is difficult to manipulate the density of the water by additions of a salt solute because the higher density salt water settles to the bottom of the container over time. The density of the dye may vary with color.
- With cooking oil as ambient fluid, dye is heavier than cooking oil and sinks as spheres to the bottom (no rings). This is a consequence of the immiscibility of the dye and the oil. Some degree of miscibility is required for the rings to form.
- To change surface tension, try mixing soap with the water or placing a thin layer of oil on top of the water before putting the dye in it.
- It is known that better rings form if the dye is more viscous. To date, an attempt has not been made to change the viscosity of the dye.
- Use of a video camera and TV to playback frames allows a more quantitative study of shape changes and primary ring speed (from the image of the cm scale next to the container). A video camera also aids students in actually seeing the vortex rings and their motions.

Reference:

A scientific study on vortex rings in fluids:

N. Baumann, D.D. Joseph, P. Mohr, and U. Renardy, "Vortex Rings of One Fluid in Another in Free Fall", Physics of Fluids A v4(3), p567, Mar 1992.

VORTEX RINGS

Name: ______________________________
Partners: ____________________________

Introduction:
What do you expect will happen when you let a drop of food coloring fall into a container of still water? Will is spread throughout the water? Will it drop to the bottom of the container as a bead? Will it do something else? Today you will have a chance to try this and observe what happens.

Procedure:
1. Fill a syringe with dye (food coloring).
2. Carefully put the syringe in the hole of the square plate.
3. Place the plate on top of the container of water.
4. Slowly push on the syringe so that a drop begins to form. The drop will release just as it touches the water.
5. In the space provided, write anything you observe that happens to the drop of dye.
6. Repeat steps 4 and 5 several times by moving the plate so that the hole for the syringe is over a different location in the water.
7. What happened when you dropped the dye into the water? Give a complete description (written or labeled diagram) for as many observations as you can make.

Observations of dye in water:

Experimental Design:

1. List at least six items that you can measure when you drop the dye in the water.

2. What one item are you going to vary in this experiment? This is known as the "independent variable."

3. What one item are you going to measure in this lab? This is known as the "dependent variable."

4. List the remaining items from question 1 that do not include the independent or dependent variable. These items must not be varied and are called the "constants" or "controls." (If they do change, it is very difficult to determine the effect of the independent variable on the dependent variable.)

5. Write a statement that describes what you think will happen to your dependent variable when you change your independent variable. This is known as the hypothesis.

6. Write an experimental procedure based on your hypothesis. Be sure to include controls, the independent and dependent variables along with safety concerns.

Data:

Conclusions/ Discussions:

1. What in your data leads you to believe that your hypothesis is try or false?

2. Did you come across anything in the lab that you felt affected the outcome of the lab? If so, what were they and did they significantly affect the outcome of the lab?

3. How could you redesign you lab to get better data?

4. Based on your data and general observations, what could you further study?

5. Using your answer to number 4, list the:
   a. independent variable

b. dependent variable

c. controls

d. hypothesis

6. Write an experimental procedure based on your answer to number 5.

7. Where do you see vortex motion in the real world?

   How are they like the vortex rings seen?

   How are they different from the rings seen?