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Educator Material

The Momentum of Swimming Dolphins

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Purpose

Students will apply the conservation of momentum to dolphin swimming. They will examine the concept of a closed system as it relates to a dolphin and the water surrounding it.

Audience

This lesson is appropriate for an introductory high school physics class.

Lesson Objectives

Upon completion of this lesson, students will be able to:

- explain and use the momentum equation (p=mv).
- describe the differences between closed and open systems.
- apply the conservation of momentum to determine an unknown velocity or unknown mass.

Key Words

closed system, conservation of momentum, conserved, mass, momentum, velocity, vortices

Big Question

This lesson plan addresses the Big Question *"What does it mean to observe?"*

Standard Alignments

- **Science and Engineering Practices**

  SP 5. Using mathematics and computational thinking

- **MA Science and Technology/Engineering Standards (2016)**

  HS-PS2-2. Use mathematical representations to show that the total momentum of a system of interacting objects is conserved when there is no net force on the system.

- **NGSS Standards (2013)**

  HS-PS2-2. Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.

Misconception Addressed

This lesson addresses a common misconception about the conservation of momentum: Velocity is conserved in a system instead of momentum. (Questions 3 and 7)

Primary Sources

- **Bite** "Swimming with the Dolphins" based on:

  Fish FE, Legac P, Williams TM, and Wei T. 2014. Measurement of hydrodynamic force generation by swimming dolphins using bubble PIV. *Journal of Experimental Biology* 217:

252-260.

- **Misconceptions**

  Singh, Chandralekha, and David Rosengrant. 2003. "Multiple-choice test of energy and momentum concepts." *American Journal of Physics* 71(6): 607–17. doi:10.1119/1.1571832.

Materials

Copies of the Student Handout and Science Bite for each student

Time

This lesson should take approximately one 50-minute class period.

Student Prior Knowledge

Students should have been introduced to the concept of momentum before this lesson. It would be helpful if students had some experience with conservation of momentum, but this lesson could serve as an introduction to the conservation of momentum.

Instructions and Teacher Tips

- **General Procedure**
  - To begin the lesson, have students watch a short (30–60 seconds) of a video clip of dolphins swimming (such as https://www.youtube.com/watch?v=LStXdttFj_o). You may want to put the video on a lower speed by clicking the settings and selecting Speed > 0.25. Students will then be able to watch the movements of the animals more closely.
  - Ask them to respond to these questions: How do you think dolphins are able to propel themselves forward in water? Why do you think it is not possible to swim through air in the same way that one can swim through water?
  - Next, have students read the introduction, either silently to themselves, or out loud in pairs.
  - Have students work together on the analysis questions, reading the Bite when instructed.
  - Have students complete the rest of the analysis questions after the Bite.
  - Review the answers to the questions with the students.
- To save class time, the introductory reading and Bite could be assigned as homework with the students completing the questions in class with a partner or in groups.
- If students have already learned about density, you can extend **Question 8** by asking them to then use the density of water to calculate the volume of water displaced by the robotic fish.

Background Information and Research Details

- **Particle image velocimetry** (PIV) is an imaging technique that scientists use to visualize water or air (fluid) movements. 2D and 3D visualizations both exist, but we'll focus on 2D underwater imaging, since that's what the researchers used here. First, the scientists seed the water with small (on the order of micrometers) particles. In the water, these particles are usually some kind of plastic or glass bead, and a 2D slice of space can be captured by selectively lighting up a plane through the tank with a laser light sheet (like in the image below). A high-speed video camera is aimed perpendicularly to the light sheet (point up at the tank from below in the image below). For the safety of the dolphins, this was modified a bit by replacing the particles with streams of bubbles coming out of a leaky air hose, which confined the bubbles to a vertical plane. Because the bubbles were only in a single plane, the laser wasn't needed, and filming could take place in natural light. Once the video is taken, a computer can track the movements of particles between each frame of video, allowing the scientists to see and measure how the water is moving around the animal.

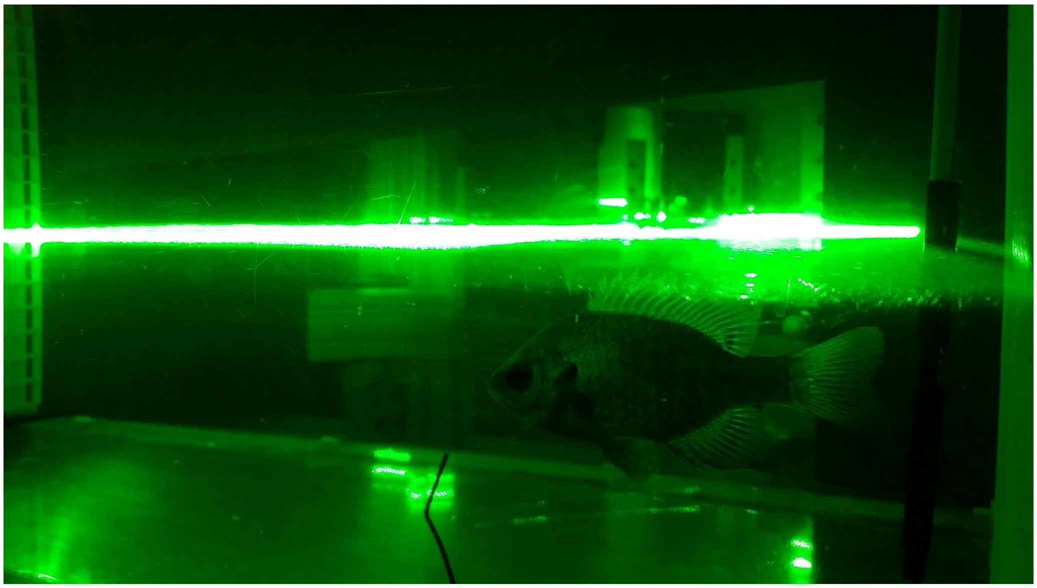

Figure 1. Side View of a PIV Experiment. When this fish swims in the light sheet at the center of the screen, scientists can film its movements with a high speed camera below the tank. By tracking the particles in the water, scientists can visualize and measure how water is moving around the swimming animal.

- In preparation for the Big Question Discussion (see below), you may want to be aware of some limitations of the bubble PIV method used by the scientists. The three big ones are that:
  1) dolphins may make some bubbles as they swim, which could be tracked as particle bubbles accidentally;
  2) the bubbles may move left and right out of the vertical plane as the dolphin swims through, which can't be tracked with a 2D camera system; and
  3) bubbles rise, so the overall upward motion of the bubbles has to be subtracted out in order to see the water movements the dolphin makes.

- You and your students might wonder about the morality of using captive dolphins for experiments like this. Here is some information you can share if this comes up. The two dolphins in this study, Primo and Puka, are both retired Navy dolphins, who were housed at the University of Santa Cruz's marine research center, which is called the Long Marine Laboratory (they since have been moved elsewhere as the Long Marine Laboratory renovates). The UC Santa Cruz facility is one of many institutions that have achieved accreditation by the Association for the Accreditation of Animal Laboratory Animal Care (AAALAC) (https://www.aaalac.org/about/index.cfm). A facility with an AAALAC accreditation not only meets the requirements for animal welfare set by law, but also has *voluntarily* chosen to hold itself to higher standards. Although the Long Marine Laboratory has an associated Discovery Center and a behind-the-scenes tour of the research center is available, they do not use dolphins for shows. According to UC Santa Cruz marine mammal scientist Terrie Williams, a co-author of the research paper, these dolphins have helped her and other scientists better care for marine mammals through training of educators and marine veterinarians, showing how strong dolphins are so that dolphin-safe fishing nets could be made, and how oceanic noise pollution can harm animal health. (See https://www.huffingtonpost.com/terrie-m-williams/the-deafening-silence-of-voicless-dolphins_b_9792232.html)
- One way this and similar research is being applied is in the care of rescued dolphins. By understanding the way that dolphins move through the water, scientists have been able to make prosthetic tails for injured dolphins in their care! Winter the Dolphin is a good example. More information about Winter can be found at https://www.seewinter.com/winter-and-hope/winter/ .
- Interestingly, other marine animals that flap their tails to swim use the same physics as dolphins, even those (like fish) that move their tails horizontally (side-to-side) instead of vertically (up-and-down)! So, the physics highlighted here also applies to whales, fish, and more. For this reason, scientists can use data from dolphins in fish-inspired robotic designs!

Big Question Discussion

This lesson should get students thinking about the Big Question "*What does it mean to observe?*" In particular, how are observations in nature different from those made in a laboratory? If you choose to delve into the Big Question, consider the following idea:

After students answer Question 9, talk to them about why completing experiments in a laboratory (or an aquarium, in this case) is necessary (allows scientists to have control over the environment and the variables they are testing). You can probe students for their thoughts on how that helps scientists make observations and how it can be limiting—in a lab we don't get to see how an animal interacts with its natural environment. For instance, the authors said that the dolphins swam normally in the tank, but perhaps there were something different that the scientists didn't notice. Was the dolphin agitated because its environment had changed or more motivated because of the food rewards from the trainers? Although there are limitations to lab work, this experiment would have been impossible outside of an aquarium. The scientists needed to be able to produce bubbles in a straight line and visualize them from under the water. They couldn't have set this up in a natural environment. Do these types of observations change how you think about what it means to observe?

Answers

1. What is the momentum of a dolphin that is hovering (not moving) in the water? How do you know?

The momentum of the dolphin is 0 kg×m/s. The dolphin has a velocity of 0 m/s and as p=mv, the momentum must also be 0 kg×m/s.

2. How is the momentum of a swimming dolphin related to the momentum of the water around it? Explain your answer.

The momentum of the dolphin must be equal in magnitude, but opposite in direction to the momentum of the water surrounding it, because momentum is conserved. If the dolphin-water system started off with 0 kg×m/s of momentum, it must end with 0 kg×m/s of momentum. If we consider the momentum of the dolphin to be positive, the momentum of the water must be negative (opposite direction) and be of equal magnitude to cancel out the momentum of the dolphin.

3. A student claims "The forward velocity of a dolphin will always be equal to the backwards velocity of the water around it." Is this statement true? Explain your answer.

The student is incorrect. The forward momentum of the dolphin will always be equal to the backward momentum of the water as momentum is conserved. Velocity is not conserved. It will only be equal if the mass of the dolphin and the mass of the water are equal.

STOP & read Science Bite:
Swimming with the Dolphins

4. Suppose that during one trial of this experiment, a dolphin was traveling at a constant speed of 3.5 m/s and the dolphin had a mass of 150 kg.
   a. What was the momentum of the dolphin? Show your work and include units in your answer.

$p = mv = (150\ kg)(3.5\ m/s) = 525\ kg \times m/s$

   b. In order for momentum of the dolphin-water system to be conserved what must the momentum of the water around the dolphin be? Explain your answer.

$-525\ kg \times m/s$

It must be equal in magnitude ($525\ kg \times m/s$), but opposite in direction (negative) in order for momentum to be conserved, since the system started off with 0 kg×m/s of momentum.

5. Researchers who study dolphin movement (and other marine swimmers!) track the movement of both the dolphin and the water around them. Why do you think they measure both? Cite evidence from the Bite.

Scientists are also interested in how the water around dolphins move, because it can help them understand the physics of a dolphin's movement. As noted in the Bite, the scientists look at features in the water's movement such as vortices. By determining the strength of these vortices, scientists are better able to understand the forces the dolphin produces.

6. A researcher finds that the momentum of a dolphin and the momentum of the water around it are not exactly equal in magnitude. Does this finding support the assumption that the dolphin and the water are a closed system? Explain your answer.

No, it does not support the assumption that the dolphin and the water are a closed system. If they were a closed system, the momentum of the dolphin and the water would be equal. There must be some outside force acting on the system.

7. The same rules we've been exploring with dolphins also apply to fish, who just move their tails side-to-side instead of up-and-down! Suppose you are a scientist who used the methods for studying dolphin swimming from the Bite to study fish, and you used your knowledge about momentum to find mass and velocity of the fish and water. But, you accidentally spilled coffee on your notes and can't read the water velocity data anymore! The data you still have on the average masses of the fish and water and the fish's average velocity are in **Table 1**.

   a. Because all your fish were swimming at a constant velocity, conservation of momentum applies. Using the data in **Table 1**, calculate the water velocity for each experiment. Show your calculations below and include units in your answer. Record each water velocity in **Table 1**.

Generally $p_{fish}=p_{water}$ therefore $m_{fish}v_{fish}=m_{water}v_{water}$ and $v_{water} = \frac{(m_{fish})(v_{fish})}{m_{water}}$

Mullet: $v_{water} = \frac{(0.011kg)(0.18\ m/s)}{0.029}$ = 0.68 m/s

Bluegill sunfish: $v_{water} = \frac{(0.0081kg)(0.20\ m/s)}{0.032}$ = 0.051 m/s

Black surfperch: $v_{water} = \frac{(0.0088kg)(0.21\ m/s)}{0.016}$ = 0.12 m/s

Brook trout: $v_{water} = \frac{(0.010kg)(0.21\ m/s)}{0.026}$ = 0.081 m/s

Type of Fish	Fish mass (kg)	Fish velocity (m/s)	Water mass (kg)	Water velocity (m/s)
Mullet (*Chelon labrosus*)	0.011	0.18	0.029	0.68
Bluegill sunfish (*Lepomis macrochirus*)	0.0081	0.20	0.032	0.051
Black surfperch (*Embiotoca jacksoni*)	0.0088	0.21	0.016	0.12
Brook trout (*Salvelinus fontinalis*)	0.010	0.21	0.026	0.081

Table 1. A Comparison of Four Fish Species. The average fish mass, average fish velocity,

and the mass of the water that moves around the fish are provided.
Sources: masses: Fishbase.org; mullet data: Muller *et. al.* 1997; surfperch data: Drucker and Lauder 2000; bluegill and brook trout: personal data (unpublished).

b. In general, how does the water velocity compare to the fish velocity? Explain why that is true.

In general, the water velocity is smaller than fish velocity, because the mass of the water is larger than the mass of the fish. In order for the water to have the same momentum of the fish, if the mass of the water is larger, the velocity of the water must be smaller.

c. You are teaching a new student researcher about fish swimming, and the student claims, “Fish and water velocity will be equal when momentum is conserved.” Are they right? Why or why not?

No, the fish and water have different masses, so they will have different velocities if momentum is conserved.

8. Imagine you are a scientist studying how marine animals swim. With an engineer partner, you are building a robotic fish that you hope to use to film fish in a local river. Before you can use the robot, the engineer needs to test to make sure the robot is working correctly. Although you could test the robot in a swimming pool, you know the robot will need to swim between narrow gaps between rocks in the river, so you and the engineer want to test the robot in a small tank. To make sure your small tank doesn’t have too little water for the robot, you want to know how much water the robot will move during the test. You know that your robot is 2.79 kg and swims at a constant velocity of 0.218 m/s. Using imaging methods in a large pool like the scientists in the Bite, you discover that the water behind your robot moves backward at 0.092 m/s. What mass of water will the robot move? Show your work.

$$p_{robot} = p_{water}$$

$$m_{robot}v_{robot} = m_{water}v_{water}$$

$$m_{water} = \frac{m_{robot}v_{robot}}{v_{water}}$$

$$m_{water} = \frac{(2.79kg)(0.218m/s)}{(0.092m/s)}$$

$$m_{water} = 6.61kg$$

9. **Connect to the Big Question**. In this experiment, researchers were investigating a natural process (the movement of a dolphin), but in a non-natural environment (an aquarium with glass walls, a trainer directing the dolphin’s swimming, and bubbles). Why was it important for the scientists to be able to make observations in this way? What are some of the limitations of this type of observation?

Without the setup in the aquarium scientists would not have been able to make accurate measurements of the water’s movement and the dolphin’s movement. The dolphin had to be perfectly positioned over the bubbles and within the view of the high speed camera in order to collect this accurate data. Such a setup does not occur in nature. This type of observation is limiting, because it is possible that the dolphin did not behave in the exact same way as it would in nature. Perhaps the training process has led it to swim differently than dolphins in the wild or the bubbles affected its swimming pattern.