BiteScis

Student Handout

The Momentum of Swimming Dolphins

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Introduction

While watching dolphins, fish, seals, or sea lions swim gracefully through the water, have you ever wondered, “How do they do that?” Sure, you’ve might have gone swimming before, but unless you’re an Olympian like Michael Phelps or Simone Manuel, you probably don’t look quite as graceful and powerful underwater. Part of the reason is that we interact very differently with a liquid like water than we do with solids. Thinking about the physics of motion for an underwater animal like a dolphin may seem complicated, but the laws of physics we know on land are still true underwater.

One of the physics principles that scientists use to explain how dolphins are able to move in the water is the **law of conservation of momentum**. **Momentum** (p) is the product of an object’s **mass** (m) and its **velocity** (v), as shown in the equation below.

$$p = mv$$

The total momentum in any closed system is always constant—momentum is **conserved**. A **closed system** is one upon which no outside forces act. If we assume that a dolphin and the water around it are a closed system, then we can connect the momentum of the dolphin and the momentum of the water around it.

Let’s think about a dolphin in an aquarium, and pretend for a moment it can hover in place. The dolphin is not moving, so its velocity (v_d) and momentum (p_d) are zero. Now, think about the water surrounding the dolphin. For the moment, imagine that the water in our aquarium is still, so again, velocity (v_w) and momentum (p_w) are zero. The total momentum in our closed system, then, is zero.

$$0 = p_d + p_w = m_d v_d + m_w v_w$$

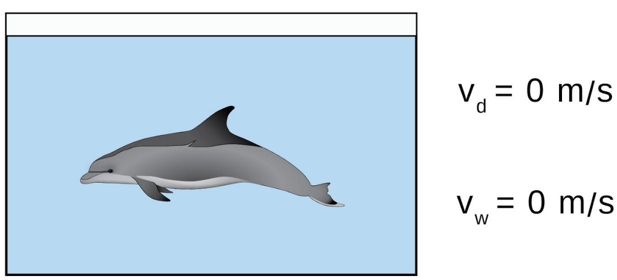

Figure 1. Side View of Dolphin Hovering in the Water. When it’s not moving at all, the momentum of the dolphin (p_d) and the water surrounding it (p_w) are both $0\ kg \cdot \frac{m}{s}$.

To swim, a dolphin bends its tail up and down. As the tail moves, it leaves one space and enters another, and pushes the water in this new space out of the way.

As the dolphin keeps moving its tail up and down, it keeps pushing water out of the way. The net water velocity v_w is no longer zero, and so the water’s momentum p_w is not zero, either. The water's momentum is, in fact, backwards! Mathematically, this means that the momentum of the water has a negative sign.

Why does the momentum of the water have a negative sign? Look at **Figure 2.** You may have noticed that the water velocity and momentum have both vertical and horizontal components. But, the vertical components cancel out as the tail beats up and down. So, we only need to focus the total horizontal component of the water's velocity over a whole up-down tailbeat motion. And that horizontal component of the water's velocity is in the backwards direction.

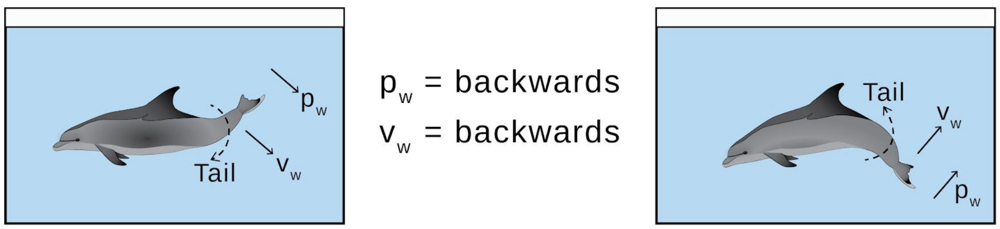

Figure 2. Side View of Dolphin in Motion. The water's velocity (v_w) and momentum (p_w) is in the backwards direction because the water is being pushed back by the motion of the dolphin's tail.

We know now the water has a backwards momentum. But, we know that in our closed system, the total momentum of the water and the dolphin has to be zero so that momentum is conserved. So, something in our aquarium has to move forward to balance out the backward momentum of the water. Here, that something is the dolphin! The momentum relationship is below.

$$0 = p_d + p_w = m_d v_d + m_w v_w$$

This relationship tells us that the forward momentum of the dolphin will have the same magnitude as the backwards momentum of the water. In equation form, this is written as:

$$m_d v_d = -m_w v_w$$

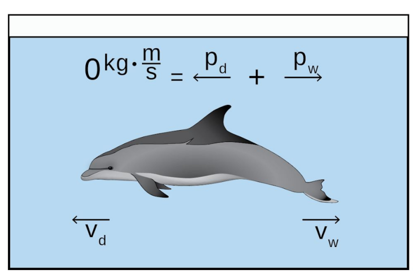

Figure 3. Momentum Vectors of the Dolphin-Water System. The momentum of the dolphin (p_d) and the momentum of the water (p_w) are equal in magnitude, but opposite in direction.

So, we see that even complicated-sounding processes, like dolphin swimming, are actually governed by simple rules of physics, like conservation of momentum.

What To Do

Answer the analysis questions below, reading the Bite when instructed.

Analysis Questions

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

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

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.

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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.

   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.

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.

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.

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**.

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	
Bluegill sunfish (*Lepomis macrochirus*)	0.0081	0.20	0.032	
Black surfperch (*Embiotoca jacksoni*)	0.0088	0.21	0.016	
Brook trout (*Salvelinus fontinalis*)	0.010	0.21	0.026	

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.

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?

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.

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?