<u>The Physics of Sailing: Teacher Guide</u>

Objectives

The goal of the lesson is to explain how sailboats work by using basic physics principles. By the end of this lesson, students should be able to identify the forces acting on a sailboat and explain how the combination of these forces result in the forward motion of the sailboat.

Lesson Prerequisites

Students should be familiar with the following concepts:

- Forces and moments
- Vector addition
- Free body diagrams
- Center of mass/center of effort

A basic understanding of fluid dynamics (i.e. laminar vs. turbulent fluid flow, resistance, etc.) might be useful, but is not necessary.

Materials

1. Pen/pencil and plenty of scratch paper for each student
2. Fan (optional, but highly encouraged for activity 2)
3. Colored pens/pencils (optional, but some students may find this helpful for free body diagrams)

Lesson Structure

Segment 1: Introduction/Initial observations
Segment 2: Lift and angle of attack
Segment 3: Balancing forces and moments
Segment 4: Apparent wind/Putting it all together

Lesson Activities

Activity 1: Predicting wind direction and direction of boats relative to the wind; initial free body diagram

- Have students pick a particular boat to focus on. It should be relatively simple to determine what direction the boat is sailing, but determining the wind direction may be more difficult. Have students look for other clues, i.e. the ripples on the water, or what direction the boats seem to be getting "pushed."
- Have students brainstorm what forces are acting on the sailboat, and draw an initial free body diagram. Encourage students to begin by simply listing the forces that may be acting on the sailboat (wind, waves, sailor's body weight,

gravity, etc.) and then have them place them on the sailboat. It may be helpful to encourage students to do a free body diagram in two different perspectives, i.e. a bird's eye view and a side or front view, in order to account for the different forces and moments.

Activity 2: Fan activity to illustrate angle of attack

- This activity is fairly straightforward. Students will hold a piece of paper in front of a fan to illustrate the concept of angle of attack. Students should notice that an angle of attack of zero does not generate any lift, while a 90-degree angle of attack gets pushed sideways. Encourage students to discuss what they think is an optimal angle of attack based on what they know from observations of airplane wings, then have them test their hypotheses with their sheets of paper and the fan.
- To reinforce the concept learned in this activity, have students draw the vector diagram of the lift generated by the flow of air over the sheet of paper. This should look similar to the diagram shown at 6:07 in the lesson video.

Activity 3: Updated free body diagrams

- Have students re-visit their initial free body diagrams. They will likely have items they'd like to change, based on the previous segments. The diagrams at 9:50 in the lesson video will be particularly helpful. Again, encourage students to do diagrams from different perspectives (bird's eye, side, front views) in order to account for the various forces acting on the boat.
- Make sure students account for the weight (placement and magnitude) of the sailors on the boat – ask if they noticed anything about the weight placement of the sailors in the video. Does it look as if they are doing anything to keep the boat from heeling over? If so, is it effective? See 9:50, 10:03 in the lesson video for examples.
- If students have a hard time visualizing what center of mass is, try defining it as the point at which an object could be supported, and balance perfectly (ex. try balancing a pencil on one finger) – where is this located on the boat? On the sail?

Activity 4: Predicting the fastest way to sail (points of sail)

- Students will watch a clip of boats sailing at several different directions relative to the wind. Direct students to pick ONE boat in the video to use for the activity to answer the following three questions:
    1. Students will draw a vector diagram for that boat that includes the boat's velocity, their predicted wind velocity, and their predicted apparent wind velocity.
    2. Based on their predicted apparent wind, and the position of the sail in the boat, have students draw diagrams to predict the angle of attack of the wind over the sail.
    3. Have students draw out several different scenarios in order to predict which direction is the fastest direction for a boat to sail relative to the

wind. Students may have to make some assumptions – for example, that the magnitude of the true wind velocity and magnitude of the boat's velocity are the same to start. However, if the apparent wind vector is maximized, it will cause the boat's velocity to increase – this is what makes it fastest to sail a certain direction relative to the wind.

Two Points to Note about the Lesson:

1. In Segment 3, I say that the wind force acts at the center of the sail. To be more accurate, the force acts at about 1/4 of the way back from the leading edge to the trailing edge of the sail.
2. Also in Segment 3, when discussing the free body diagram at 8:48, I should say: "the moment is proportional to the force and the PERPENDICULAR distance to the point where it is aplied." This is labelled correctly on the displayed free body diagram.

Challenge Questions:

1. Why do some boats have a lead (weighted) centerboard?
    - Have students consider how the weight distribution of the sailboat would be different in this case. For example, where the center of mass would be located, and how that would affect the forces and moments acting on the sailboat? Concentrating more weight in the keel lowers the boat's center of mass, increasing the moment that "rights" the boat against the
2. What is it about the concept of apparent wind that allows some boats to sail faster than the true wind speed?
    - Have students question what will happen if, as we assumed above, the apparent wind vector is maximized and the boat's forward velocity increases. This will in turn cause the apparent wind vector to increase, which will cause the boat's forward velocity vector to again increase, leading to what is called the "acceleration effect." All boats will experience this to some effect but will eventually reach an equilibrium state where the boat's forward velocity is still not as fast as the true wind speed; however, some racing boats are very light and hydrodynamic and are able to reach an equilibrium condition in which they are sailing faster than the true wind speed.