Transcript for the BLOSSMS Lesson

An Introduction to the Physics of Sailing

_[MUSIC PLAYING]

Do you ever wonder how people manage to sail all the way around the world without a motor? How did they get where they wanted to go, regardless of the wind direction? Have you ever watched a sailboat race and wondered why, on earth, it looks like they were all sailing in different directions? And did you know it's actually possible for some boats to sail even faster than the wind without a motor or propeller? Today, we're going to solve these mysteries, using basic principles of physics. We'll use what we already know about vectors and trigonometry, forces and moments, and a little bit of fluid dynamics, in order to figure out how, on earth, a sailboat works.

Welcome to the MIT Sailing Center, on the scenic Charles River. Before we begin our lesson, let me introduce myself. My name is Emma Ferris, and I'm a graduate student at MIT, studying mechanical engineering, with a focus on ocean engineering. In college, I studied Naval architecture, or ship design. One of the reasons I've chosen to study these topics is because I've been sailing since I was 10 years old.

I really enjoyed learning about new technologies that make boats go faster and make my favorite sport even more exciting. I've also spent many years teaching kids how to sail and love sharing my passion for engineering and sailing with others. Now that we've gotten that out of the way, let's begin with the brainstorming activity.

Take a look at the several different clips of sailboats here at the MIT Sailing Center. As you watch the video, see if you can answer the following questions. What direction does it appear the wind is coming from? What direction does it appear that boats are headed relative to that wind direction? Using what you already know about forces, what forces do you think are acting on the sailboat? See if you can draw a free-body diagram that includes those forces.

Welcome back. What did you all think of activity one? You might have noticed that there seemed to be a lot of forces acting on a sailboat, and it can be pretty confusing. Watching the clips might also have helped to clear up some common misconceptions about how a sailboat works. It seems as though sailboats would only be able to sail when the wind is coming from behind them and pushing them forward. But you probably noticed from the videos that sailboats are able to sail at many angles relative to the wind direction. We'll learn more about this in the rest of the lesson. From your brainstorming activity, it's pretty clear there are a lot of forces at work that cause a sailboat to move forward. Forces underwater, forces on the sail, and even the force of the sailor's weight in the boat all play a role.

As we start to make sense of it all, let's remember that vectors have both magnitude and direction, velocity and acceleration, and forces and moments can all be represented by vectors. Let's also remember some basic rules of physics-- that an object in motion stays in motion unless acted upon by an outside force and that every action has an equal and opposite reaction. Keep these rules in mind as we go through the lesson and as we start to look at the forces that are acting on the sail.

You may be familiar with the concept of lift and the way airplanes work. Well, the same principles are what get sailboats moving forward, except, in this case, the sail is the wing. If you're not familiar with lift or how airplanes work, have no fear. We'll break it all down and try and figure out how it applies to sailboats.

First, let's recall that an airplane wing has lots of surfaces that this pilot can control and adjust. These surfaces change the way the air flows over the wing, which, in turn, changes the direction and magnitude of the lift force vector. As the pilot gets ready to take off and as the plane starts moving forward, air starts flowing over the wing. But because the wing is at an angle to the ground, the air doesn't flow over the top and bottom surfaces of the wing in quite the same way. The result is that the air at the top of the wing and the air at the bottom of the wing has to travel a different distance to get to the edge of the wing. This means that the air at the top and bottom of the wing are at slightly different pressures, resulting in an upward force, called lift.

Once the plane starts going fast enough and the pressure difference between the top and bottom surfaces gets big enough, the lift force is big enough to lift the whole plane off the ground. The angle of the wing with respect to the oncoming airflow is very important, and it's called the angle of attack. These same principles are true for a sailboat, except, as I said before, the sail is the wing. We just rotate everything 90 degrees, since an airplane wing is parallel to the ground, and a sail is vertical.

First, let's note where the wind is coming from and then the direction the boat is pointing. Now I'm going to demonstrate some sailing techniques. We can confirm that the wind is indeed blowing over the sail the same way the air flows over the airplane wing. As you can see, I just had to get enough air flowing over the sail to generate enough lift to move forward. Also notice I had to pull the sail in to get going. That's because I can control the angle of attack of the wing. If I do not adjust the sail properly, the angle of attack won't be correct.

To illustrate this, let's watch what happens when I pull in the sail too tight or let it out too far. When I let the sail flap in the wind, the sail was operating at a zero degree angle of attack. There's no lift force generated, because the wind just flows directly over the sail. When I pulled in the sail too tight, the wind had a hard time flying over the backside of the sail and created a lot of turbulence. So the lift vector was very small, so the boat was moving forward slowly.

Now we can confirm that, when sailors adjust the sail, they are really adjusting the angle of attack. And it's important to have the right angle of attack between the wind and the sail in order to move forward. In the next activity, we'll continue to investigate the concept of angle of attack and lift for ourselves.

Take a piece of paper and hold it in front of a source of wind. You can either blow on it or hold it in front of a fan. Try holding the paper perpendicular or parallel to the source. What happens? What about if you hold the paper at a very small angle to the source?

In the first activity, we predicted what direction the wind was coming from and what direction both were pointing, relative to the wind. And we just learned how the wind flows over the sail to generate the lift force. You might have noticed from the last activity that if the piece of paper is parallel to the fan, there's no upward force. And if the paper is at an angle to the fan, you feel a force perpendicular to the paper.

But there's still something here that doesn't seem to add up. If the angle of the paper relative to the fan is small, the lift vector generated by the wind flowing over the paper doesn't really seem that big. But in the first activity, we saw boats sailing perpendicular to the wind. How was the lift vector big enough to propel them forward? And why don't they just get blown over sideways? Let's take a closer look.

Well, we already know that both force and velocity can be represented as vectors, meaning they have both magnitude and direction. We also know that an object that has a constant velocity, or a zero acceleration, is in an equilibrium condition. You might have also noticed, in activity one, that some of the boats seemed to be sailing perpendicular to the wind. So if the boat is moving forward at a constant velocity, there must be some force acting on the boat that counteracts the force of the wind on the sail and prevents the boat from flipping over.

Take a look at this model sailboat. Keeping in mind that the force from the wind acts at the center of the sail, do you see anything on the model that might counteract that force? If you guessed this thing, you're correct.

Let's see how it works on a real sailboat. What happens if we try to sail away from the dock without the centerboard. I don't think we'll make any progress sailing like that. Now let's try sailing with the centerboard down. And what do you know, we're off to the races. When the wind blows on the sail, the boat experiences a force at the center of the sail pushing it sideways.

As you all already know, a force can cause a moment, which is dependent on the magnitude of the force and the distance from the point where it is applied and the center of mass of the object it is acting on. In this case, the force located at the center of the sail is some distance away from the center of the mass of the boat. So this force causes a moment, which causes the boat to rotate about its longitudinal axis. But if we put down the centerboard, when the wind pushes on the sail and causes the boat to start to rotate, the addition of the board pushes on the water. This means the water responds with the reaction force that acts upon the centerboard, shown here.

Another added bonus of the centerboard is that, like the sail, it also acts as a foil. The water flowing over the centerboard also generates lift. And this lift, in addition to the lift generated by the airflow over the sail, helps the boat move forward.

But you're probably thinking, wait, what about when it's really windy? Won't the boat still want to tip over, because the force vector from the wind is bigger? Let's remember our brainstorming activity, where we drew free-body diagrams of all the forces we thought were acting on the boat. Based on what we just learned, let's try and make some changes to our free-body diagrams.

For example, how exactly does the sailor's weight placement affect the balance of forces and moments present on the sailboat? Keep in mind where the sailor's center of mass might be located. Based on what we learned about lift from the previous segment, what forces do you think are generated by the centerboard?

For an added challenge, consider this-- why do some boats have a weighted centerboard? How does this change the weight distribution of the sailboat? Where would the center of mass be located? And how would that affect the force and moments acting on the sailboat?

The previous lesson section and activity should have helped clear up any confusion about what forces are acting on the sailboat to keep it from sliding sideways or tipping over. But there are still two questions we really haven't answered. How are boats able to sail at different directions relative to the wind? And how are some boats able to sail faster than the wind? These two questions are well answered by using the concept of apparent wind.

Let's say you're riding a bike on a windy day. You start riding with the wind blowing at you from the side perpendicularly. As you ride faster and faster, soon you only feel the wind on your face. The wind you feel on your face is what we call the apparent wind. It's a combination of the true wind, the wind blowing at you from the side, and the wind that you feel that results from your forward motion. If you're moving faster than the wind is blowing, then the sum of the two vectors seems to come more from the direction in which you are riding.

Let's take a look at one particularly confusing case, the case where the wind is coming from directly behind a sailboat. In this case, the boat feels the wind pushing it from behind, but it also feels the wind due to its forward motion. Because the wind vector felt by the boat due to its forward motion is in the opposite direction as a true wind, the apparent wind factor is still coming from behind that boat, but is very small, meaning that, for this wind direction, the sailor should adjust his or her sails to about here.

Based on what we've learned about how sails work for other wind directions, that flow over the sail creates lift, which pushes the boat forward, this might be confusing. In this case, there's not a lot of flow over the sail that creates lift. In this case, the dominant force moving the boat forward is the force of the wind pushing the boat from behind.

Knowing what you know now, what do you think is the fastest direction for a boat to sail, relative to the wind? Is it when a boat is pointing directly into the wind or directly behind? It when the wind is perpendicular to the boat or some angle in between? Take a look at the footage of boats sailing here at MIT, and keep in mind where the wind might be coming from, what direction the boats are heading relative to the wind direction, and what you think the angle of attack of the sail might be, to help you complete this activity. For an added challenge, consider this-- what is it about the concept of apparent wind that allows some boats to sail faster than the true wind speed?

What did you think of the previous activity? Were your findings different from what you expected? This activity should have helped clear up a few common sticking points. As you can see from the diagram on the screen, you cannot sail directly into the wind. It is fastest to sail perpendicular to the wind.

The lessons you've learned here today have many more advanced applications. You could use what you've learned to answer more questions about sailing. For example, you might be wondering-- today, we learned how a boat goes in a straight line, but we don't know how it turns. How does the rudder work? What forces might be acting on it?

For even more of a challenge, consider this. Sailors can actually use their knowledge of forces and moments to steer a boat without ever touching the rudder. But how? Also, one piece of technology that has been revolutionizing water sports recently is the addition of hydrofoils. They can be added to surfboards, racing sailboats, speedboats, and kite boards, just to name a few.

But how do they work? Why do boats with hydrofoils go so much faster than boats without hydrofoils? These are just a few questions you could ask to continue challenging yourself with this topic further. I hope you enjoyed this lesson. I had a great time making it. And I hope it made this confusing sport make a little bit more sense. And congratulations, you're all now one step closer to being able to sail around the world.

Thank you for choosing to use this lesson. I chose to do this lesson because, while I've always been passionate about sailing, I realized, at some point, that although I knew how to sail, I didn't understand how sailing actually worked. So I did some investigation of my own. I couldn't believe I'd been sailing for so long and had never actually thought about knowing how physics was involved in making a boat go forward.

At the time, I'd actually been a sailing instructor for several years. And I realized I'd been teaching people how to sail without teaching them how their specific actions they did in the boat had an effect on the boat. The physics of how sailboats work, like the physics of how an airplane works, isn't very intuitive. But it makes a lot of sense once you break it down into individual forces and moments.

I also chose to do this lesson because I think the physics of sailing is a great way to illustrate a bunch of different physics concepts in a fun and interesting way. A lot of people have a basic understanding of how an airplane works, but fewer understand sailing, even though it's not all that different. The lesson also has a lot of opportunities for students who are interested to pursue the topic further.

The physics of sailing is an important lesson, because it provides a scientific explanation for a phenomena that most students probably have not really thought about. It's also a great way to teach basic mechanics, because it makes use of so many principles-- vectors, forces, moments, free-body diagrams, and even a little bit of fluid dynamics. I think two of the most interesting parts of this lesson is that it can be used to teach the concept of lift and makes evident to students that the sail on a sailboat is a lot like the wing on an airplane. They're both just foils in a fluid.

The second part of this lesson that I think is really interesting is that it can be used to introduce concepts of fluid dynamics. For example, I don't talk about drag forces in this lesson, but this concept could be introduced as a follow-on topic. Students might also question how boats that are really heavy can stay afloat. These types of questions could lead to discussions on fluids statics, buoyancy, and more fluid dynamics.

The learning objectives for this lesson are for students to apply what they know about mechanics to a real world problem. There are many facets to this problem beyond what is covered in this lesson. But the main goal should be for students to identify the forces acting on the sailboat, to be able to draw a free-body diagram of the forces acting on the boat, to be able to identify where the forces are acting on the boat,and this leads to the next goal: to be able to identify the moments present in this situation, the forces acting on the boat that are not located at the center of mass. The last objective is for students to learn about the basic principles of lift and fluid flow over a foil.

Prior to this lesson, students should be comfortable with several basic concepts of mechanics. They should be able to add vectors, draw a basic free-body diagram, estimate the center of mass of an object, and be able to do basic force and moment calculations; so for example, knowing that an object at rest, or at constant velocity, will have a total force balance of zero, and an object that is not rotating will have a moment balance of zero.

For the first activity, students will watch clips of boats sailing at the MIT Sailing Center. Have students answer the following questions. What direction does it appear the wind is coming from? What direction does it appear the boats are headed relative to the wind direction? It's probably best, at this point, to go clip by clip to answer these questions and have students draw vector representations of the wind direction and the boat direction on the whiteboard or blackboard or on paper. Prompt the students, to see if they can brainstorm what forces are acting on the boat and where they are applied. Basically, brainstorm what a free-body diagram of the boat might look like.

In activity two, students will take a piece of paper and hold it parallel to a stream of air. This can be either a fan, or the students can blow on the piece of paper. Ask the students, what happens when the paper is perpendicular to the wind? What happens if the paper is parallel to the wind? What happens if the paper is at a very small angle relative to the wind?

Do the students feel a force acting up or down on the paper? Again, see if students can draw a free-body diagram of the forces acting on the paper at this small angle, and include any forces they could feel acting on the paper, such as lift. For an added challenge, ask the students, how did the amount of upward force change as the angle of the paper relative to the wind changed?

For the third activity, students will revisit their free-body diagrams from the first activity, answering the following questions. Based on what was just presented, how exactly does a sailor's weight placement affect the balance of forces and moments present on the sailboat? Keep in mind, or tell students to keep in mind, where the sailor's center of mass might be located, in addition to the center of mass of the sailboat. If students have a really hard time visualizing what center of mass is, try defining it as the point at which an object can be supported and balanced perfectly. For example, try balancing a pencil on one finger. Where might this point be located on the boat and on the sail.

Based on what was learned about lift from the previous segment, ask students what forces they think are generated by the centerboard. Do they think these forces factor into the free-body diagram? This can be tricky, because, in addition to providing a side force that helps keep the boat stable, the centerboard experiences lift, because the water is flowing over it. If it is confusing, try breaking up the problem. Determine the side force generated over the centerboard and then the lift.

For an added challenge, ask students to consider the following questions. Why do some boats have a lead, or weighted, centerboard? Keep in mind 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.

For the last activity, based on the previous section, have students predict what direction relative to the wind they think is the fastest way to sail. Is it when the boat is pointing directly into the wind, when the wind is pushing the boat from behind, or when the boat is sailing perpendicular or at some other angle to the wind? Students should test their hypothesis by drawing the wind vector, the boat's direction vector, and determining the magnitude of the apparent wind vector by adding these vectors together.

Students should assume a wind speed vector is twice the magnitude of the boat's velocity. This begs the question, well, if the apparent wind vector is larger, then doesn't that make the boat go faster? And the answer is yes, to a point. The boat will accelerate to an equilibrium condition. However, students should try to maximize the apparent wind vector, given these magnitudes.

For an added challenge, ask students what it is about the apparent wind vector that allows boats to sail faster than the true wind speed. During this activity, students will also review sailing footage, to further explore how the sail is pulled in and out in order to maximize speed. For a specific clip, determine where the wind is coming from, where the boat is headed, and the angle of attack of the sail, to see how the sail is adjusted for different wind directions in order to maintain the optimal angle of attack.

One option for teachers who would like to extend the activity period to both before and after the lesson could encourage students to design and build their own sailboats from readily available materials, such as Coke bottles, pieces of paper, pencils, et cetera. Students can design a boat based on their preconceptions of what a sailboat should look like. Then, after the lesson, students can redesign their sailboat and see what they would change, in order to apply what they've learned from the lesson. Information about this activity is downloadable from the Blossoms website. I really hope that you and your students enjoy this lesson as much as I enjoyed making it.

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