Theories of Lift

Session Time: Two, 50-minute sessions

DESIRED RESULTS

ESSENTIAL UNDERSTANDINGS

The principles of aerodynamics allow an aircraft to fly, yet those same principles limit its ultimate performance and capabilities. (EU2)

Safe and efficient aviation operations require that pilots use math, science, and technology. (EU4)

A deep understanding of how an aircraft operates, which enables a pilot to fly an aircraft to its maximum capabilities in both normal and abnormal situations. (EU5)

ESSENTIAL QUESTIONS

1. Do we really understand lift?

LEARNING GOALS

Students Will Know

- How Bernoulli's Principle and Newton's Third Law work together to create lift.
- Why the incorrect theories of lift are not accurate.

Students Will Be Able To

- *Summarize* why the development of lift is such a complicated concept. (DOK-L2)
- *Explain* how lift is created. (DOK-L2)
- *Analyze* three misconceptions about lift. (DOK-L4)

ASSESSMENT EVIDENCE

Warm-up
Students are provided several incorrect and correct theories of lift. Each group will prepare and deliver a brief explanation of their assigned theory and vote on the theory that they think makes the most sense.

Formative Assessment
Students will perform a "quick grade" activity to check their understanding of lift. On a piece of paper *without their name*, each student will explain, in writing, how lift is created. Collect the papers, then immediately mix them up and hand them back out to students. Students will "grade" the explanation they receive by writing comments either reinforcing or correcting the explanation.

Summative Assessment
Students will write a script for a YouTube video that teaches viewers why the incorrect theories of lift are in error by referencing how lift is actually created.

LESSON PREPARATION

MATERIALS/RESOURCES

- Theories of Lift Presentation
- Theories of Lift Student Activity 1
- Theories of Lift Student Activity 2
- Theories of Lift Teacher Notes 2

Floating Ball Demonstration (per class)

- Hair dryer
- Ping pong ball
- Optional: one bendable straw and ping pong ball for each student

Magic Balloon Experiment (per team)

- 2 balloons
- Two (2) 12” pieces of string
- Tape
- Straw

Airfoil Designs Test (per team)

- Several pieces of 8-” x 11” paper
- Tape
- Plastic straw (cut in thirds)
- String
- Scissors
- Single-hole punch
- Electric box fan or other small variable speed fan (per class)

YouTube Storyboards (per student)

- Poster boards
- Markers

LESSON SUMMARY

Lesson 1: Theories of Lift
Lesson 2: Airfoils and Lift Production
Lesson 3: Calculating Lift
Lesson 4: Aerodynamic Stalls

At the start of this lesson, students will be introduced to five theories of lift and asked to explain which ones they think are the most plausible. They will then briefly discuss the importance of lift for aircraft and watch a video that shows aircraft designs that failed to produce adequate lift for flight. After discussing the challenges associated with creating lift, students will watch a short video that shows how air moves around a wing in flight.

The teacher will then revisit different theories of lift, providing historical context for how and when some of them were developed. The teacher will demonstrate lift in action using a ping pong ball and a hairdryer. Students will then have the opportunity to perform two simple lift experiments and propose which of the five theories of lift best explains their observations.

The teacher will then show a video demonstrating how two of the theories--Bernoulli's Principle and Newton's Third Law--work together to produce lift. The teacher will go on to explain why the remaining three theories of lift are not correct. The teacher will then evaluate the students' understanding of lift and correct any misconceptions.

To conclude the lesson, students will create a script and storyboard for a YouTube video that explains the problems with the three incorrect theories of lift.

BACKGROUND

Lift is a complex concept that has taken scientists generations to unravel. Even today, scientists continue to make new discoveries regarding how lift works.

In this lesson, students will be introduced to five different theories of lift. Through the course of the lesson, they will have the opportunity to evaluate each of the theories, leading them to the conclusion that two of the theories, Newton's Third Law and Bernoulli's Principle, work together to explain lift, while the remaining three theories are incorrect.

Each of the five theories is outlined below.

The Equal Transit Time or Longer Path theory is a widely disseminated, but inaccurate, theory of lift. This theory posits that the molecules of air flowing over the top of a wing must travel faster than the molecules of air flowing beneath the wing in order to meet at the trailing (back) edge. The essential problem with this theory is that it is based on the false idea that molecules of air arriving at the leading edge (front) of the wing at the same time must also arrive at the trailing edge of the wing at the same time.

The Skipping Stone theory is another popular, but inaccurate, theory of lift. It proposes that lift is produced because air hitting the underside of the wing is deflected downward, pushing the wing up in a simple action-reaction cycle much like the one produced by skipping a flat stone across the surface of the water. The essential problem with this theory is that it does not accurately reflect the physical properties of the fluid (air) through which the wing is moving. This theory also ignores the role of other surfaces, including the upper surface of the wing, in producing lift.

A third common, but incorrect, theory of lift is known as the Venturi theory. It suggests that air flowing over the top of a cambered wing surface is compressed, as in a Venturi tube, and therefore moves more quickly than air that is not compressed. The primary problem with this theory is that it is based on an incorrect assumption that the top wing surface acts as a Venturi tube. Without compressing the air from both sides, as in a tube, the air flow does not produce the velocity field needed to explain lift.

Bernoulli's Principle is the first of two correct theories of lift students will be introduced to in this lesson. Bernoulli's Principle states that density and pressure are inversely related for fluids in an ideal state. In practical terms, this means that a slow-moving fluid exerts more pressure than a fast-moving fluid. When air moving over the top of a wing surface travels faster than air moving over the bottom of the wing surface, pressure above the wing is reduced, producing lift.

Newton's Third Law of motion is the second correct theory of lift students will be introduced to in this lesson. It states that for every action there is an equal and opposite reaction, so that a downward force is met with an equal and opposite upward force. When an airfoil bends air traveling across its surface downward, this action results in an equal and opposite upward force.

Bernoulli's Principle and Newton's Third Law of motion work together to explain how lift is produced by an aircraft wing. Lower pressure above the wing and the upward reaction force caused by air being pushed downward combine to help the wing develop lift.

DIFFERENTIATION

To support a deep understanding of the material presented in the **EXPLORE** section, have students form small groups and participate in reciprocal teaching by using the strategies of predicting, generating questions, clarifying, and summarizing to guide small group discussions on the topic. This allows students to construct meaning from text and build social awareness and relationship skills.

To support student comprehension of new information in the **EXPLORE** section, provide a graphic organizer such as a Know/Want-to-Know/Learned (KWL) for students to complete regarding the information on the different theories of lift. This will allow students to better understand the structure of new information and also connect working and long-term memories.

LEARNING PLAN

ENGAGE

Teacher Material: Theories of Lift Presentation
Student Material: Theories of Lift Student Activity 1

Slides 1-3: Introduce the topic and learning objectives of the lesson.

Slides 4-5: Conduct the **Warm-Up.**

Warm-up

Split students evenly into five groups and provide each group one of the five common theories of lift found in **Theories of Lift Student Activity.** Each group should read its theory and then prepare a brief explanation of the assigned theory. Following brief presentations to the class, students vote on which theory they find most plausible. Using the top responses, ask the students to explain their reasoning.

Note: Do NOT reveal which of the theories are correct. Through the course of the lesson, students will come to a conclusion about which two theories work together to create lift.

[DOK-L2; *explain*; DOK-L3; *assess*]

Slide 6: Explain to students that one challenge for successfully designing aircraft is knowing how to effectively create lifting surfaces. Ask them why creating lift is such an important part of the aircraft design process? The answer is that an aircraft simply won't fly without it.

Show students an outtake video of early aircraft designs and attempts to create lift. If time is short, the video can be stopped after a few failed attempts. Ask students to make notes of the types of problems these early designers had. Why do the students think it was so difficult to create successful aircraft? Why are we still working to develop a precise understanding of lift today?

- "The First Flying Fails That Changed History" (Length 4:57)
  http://video.link/w/ukSd

Questions

What types of problems did these early designers have?

Not enough power from the engines, or engines that were too heavy compared to the power they created; wings that were not shaped for optimal lifting efficiency; bird-like structures that were not capable of flight; aircraft structures that failed as a result of induced stresses.

Why do you think it was so hard for them to create a successful aircraft?
Perhaps they didn't yet understand the science; more research was needed to find an effective way to create lift with the technology available to them.

We are still working to develop a precise understanding of lift. Why?
Lift is very complicated and there is no one easy answer to how it is created.

Slide 7: Generating lift and air flow are complicated. The video on this slide shows both the downwash created by a wing, as well as the wingtip vortices that extend off the tip of the wings. This is what had to be understood by early investigators, who didn't have the benefit of videos showing motion. For more than 100 years before the Wright Brothers' first flight, scientists were working on understanding the forces involved.

Show students a video that demonstrates the wingtips vortices spiraling off the end of the wings of an airplane flying through the clouds. The is air getting pushed down and rotated/swirled behind the aircraft. Point out how complex the flow is around the wings, the vortices, and the downward wash. It is only relatively recently designers had access to this type of imagery. Although aerospace engineers have understood the science and math behind lift for some time, we could only infer and imagine.

Ask the students to identify which of the theories of lift might be supported by what they observed during this video. Start the video at the 5:30 mark.

- "Incredible Wingtip Vortices!" (Length 00:45)
  http://video.link/w/ZISd

Questions

Students may say that this video demonstrates the "Skipping Stone" theory because the airflow is striking the lower surface of the airfoil and pushing the airfoil upward; "Newtonian" theory because the airfoil is bending the airflow downwards resulting in an equal and opposite reaction upwards (lift).

EXPLORE

Teacher Material: Theories of Lift Presentation

Slides 8-9: Sometimes referred to as "the father of aviation," Sir George Cayley was one of the first scientific investigators of flight. He understood the importance of cambered wings, constructed the first flying model airplane, and designed the first glider that carried a human aloft.

Slides 10-11: Many people worked on developing the theory of flight, those who were successful weren't just making it up.

The Wright Brothers built an advanced wind tunnel and used advanced math (all without a college education!). They were bicycle mechanics. But they had a dream, and the desire to pursue it, so they taught themselves the mathematics they needed to make calculations.

The Wright brothers relied heavily upon the research and information discovered by aviation pioneers before them. They studied the learning and the challenges encountered by Otto Lilienthal, Octave Chanute, George Cayley, Samuel Pierpont Langley, and others.

Unlike the pioneers before them, they solved three major challenges that allowed for the first powered, controlled flight: Creating a wing with sufficient lift; balancing and controlling the airplane; and developing an engine with sufficient power. They became self-taught engineers by employing their own method of testing ideas and designs, analyzing the data, then refining the design based on those results. It was the first time that "engineering practices" were used in aircraft development and they are still used today!
Wilbur and Orville conducted preliminary tests on as many as 200 different model wing shapes as they perfected the operation of their wind tunnel. They made formal tests and recorded data on nearly 50 of these.

The wind tunnel and instruments the Wright brothers designed worked accurately and efficiently. They designed their wind tunnel to determine two specific values in the lift and drag equations: the coefficients of lift and drag. Not only were they able to check the accuracy of Otto Lilienthal's table of coefficients for his single wing shape, but they also collected data for dozens of other shapes. This allowed them to select the most efficient wing for the aircraft they wanted to build.

Slide 12: Daniel Bernoulli was from a family of prominent Swiss mathematicians. His theory, now known as Bernoulli's Principle, was first concerned with how the speed of blood flow in the body affects blood pressure. Bernoulli's Principle is also responsible for the working of a carburetor, which mixes fuel and air in gasoline engines before injecting the mixture into the cylinder for combustion.

Slide 13: In a closed system, Bernoulli discovered that the restricted area of a Venturi tube results in a higher speed of the flow, creating a lower pressure. In other words, density and pressure are inversely related for fluids in an ideal state. In practical terms, this means that a slow-moving fluid exerts more pressure than a fast-moving fluid.

Slide 14: Bernoulli's Principle predicts faster airflow over the top of the wing, creating an area of lower pressure on the top and higher pressure underneath the wing, the result being lift.

Slides 15-16: Newton's Third Law of Motion says that for every action there is an equal and opposite reaction, so that a downward force is met with an equal and opposite upward force. When an airfoil bends air traveling across its surface downward, this action results in an equal and opposite upward force.

EXPLAIN

Teacher Materials: **Theories of Lift Presentation**, **Theories of Lift Teacher Notes 2**
Student Material: **Theories of Lift Student Activity 2**

In the remainder of this session, students will demonstrate different forms of lift creation using everyday objects from the school or house.

Slide 17: Floating Ball Demonstration

In this activity, students will observe a demonstration of the Bernoulli Principle and Newton's Third Law of motion. It will involve placing a ping-pong ball into a stream of air generated by a hair dryer and exploring the conditions under which the ball floats in the air. This demonstration can also be supersized with a leaf blower and a beach ball.

Ask the students if the hairdryer can make the ping-pong ball float. Turn on the hair dryer and aim it at the ceiling. Place the ping-pong ball directly over the nozzle of the hair dryer. The ball will appear to be floating in the air.

- Ask the students to explain what the ball is floating on.
  Answer: High velocity air from the hair dryer.
- Ask the students which is moving faster, the air coming from the hair dryer, or the air around it?
  Answer: The air from the hair dryer.

- Thinking back to Bernoulli's principle, how is the faster moving air coming out of the hair dryer affecting the pressure within the airflow? How about the air outside of the stream?
  Answer: The pressure is lower within the stream of air coming from the hair dryer. Outside the airstream, the pressure is higher.
- When the hair dryer is pointed straight up, what is keeping the ball from falling down onto the hair dryer?
  Answer: Gravity is pulling the ball down towards the hair dryer. The air is rushing up and pushing on the bottom surface of the ball. The upward rising air is creating an equal and opposite reaction that causes the ping-pong ball to "float." This is an example of Newton's Third Law.
- Ask what will happen if the hair dryer is turned off.
  Answer: Turning the hair dryer off causes gravity to make the ball fall. Then turn the hair dryer on, float the ping-pong ball, and tilt the hair dryer at a progressively steeper angle. The point where the ball drops is the point where gravity exceeds lift. Point out that the ball stays in place as long as the forces are in balance. When equilibrium is lost, the greater force takes over.
- Ask the students to explain why the ping-pong ball stayed within the airflow even when the hair dryer was tilted?
  Answer: The slower moving air around the hair dryer is holding the ball in place because it exerts more pressure than the faster air coming from the hair dryer.

Ask the students to identify which of the theories of lift might be supported by what they observed. Hopefully they will recognize Bernoulli's Principle because the increased velocity of the air is creating low pressure around the ball and allowing it to rise. The greater air pressure in the slower moving air outside the stream from the hair dryer holds the ball in place. They might also theorize that Newton's Third Law is keeping the ball aloft within the stream of air.

Slides 18-19: Magic Balloons experiment

Students will perform two experiments in which air flows around different surfaces and observe the results. Students should determine which theory or theories of lift best explain their observations in each experiment. Students should be prepared to share their ideas with the class.

Provide each student a copy of **Theories of Lift Student Activity 2.**

In the first experiment, Magic Balloons, the students will observe the effects of increasing the velocity of air between two balloons. This is a demonstration of Bernoulli's Principle. Divide the students into groups of two to three and ask each team to follow the directions on the student activity sheet. Ask the students to record their observations on the activity sheet and choose the theory of lift they think best explains what happened.

In the second experiment, students will learn how the shape of an airfoil (camber) and its angle to the airflow (angle of attack) influences how well that airfoil develops lift. Ask the students to record their observations on the activity sheet and choose the theory of lift they think best explains what happened.

Answers to the questions can be found in **Theories of Lift Teacher Notes 2**.

EXTEND

Teacher Material: [Theories of Lift Presentation]

Slide 20: Show students a video that demonstrates that Bernoulli's and Newtonian's explanations work together to create lift. Point out how the airflow is faster over the top of the airfoil and slower under the bottom. Also point out how the airflow both above and below the wing is being bent downward. In other words, both the top and bottom of the airfoil are pushing the air down. This shows that both Bernoulli and Newtonian explanations of lift simultaneously occur in the production of lift.

- "Wing Lift Holger Babinsky" (Length 1:13)
  http://video.link/w/1kSd

Slide 21: In other words, there are airflow differences in speed and pressure above and below the wing that follow Bernoulli's Principle. Simultaneously the airflow being deflected down by upper and lower surfaces is evidence that an equal and opposite reaction is occurring according to Newton's Third Law.

Slide 22: The following slides explain why the remaining three theories of lift production aren't true.

The Equal Transit Time or Longer Path theory is a widely disseminated, but inaccurate, theory of lift. This theory posits that the molecules of air flowing over the top of a wing must travel faster than the molecules of air flowing beneath the wing in order to meet at the trailing (back) edge. The essential problem with this theory is that it is based on the false idea that molecules of air arriving at the leading edge (front) of the wing at the same time must also arrive at the trailing edge of the wing at the same time.

Slide 23: The Skipping Stone theory is another popular, but inaccurate, theory of lift. It proposes that lift is produced because air hitting the underside of the wing is deflected downward, pushing the wing up in a simple action-reaction cycle much like the one produced by skipping a flat stone across the surface of the water. The essential problem with this theory is that it does not accurately reflect the physical properties of the fluid (air) through which the wing is moving. This theory also ignores the role of other surfaces, including the upper surface of the wing, in producing lift.

Slide 24: A third common, but incorrect, theory of lift is known as the Venturi theory. It suggests that air flowing over the top of a cambered wing surface is compressed, as in a Venturi tube, and therefore moves more quickly than air that is not compressed. The primary problem with this theory is that it is based on an incorrect assumption that the top wing surface acts as a venturi tube. Without compressing the air from both sides, as in a tube, the air flow does not produce the velocity field needed to explain lift.

Slide 25: Conduct the **Formative Assessment**.

Formative Assessment

Students will perform a "quick grade" activity to check their understanding of lift. On a piece of paper without their name, have each student explain, in writing, how lift is created. Collect the papers, then immediately mix them up and hand them back out to students. Students will "grade" the explanation they receive by writing comments either reinforcing or correcting the explanation. Review the correct answer with the class. Collect the papers, place them in a pile, have students get their own paper, write their name on it, and return it to the teacher for credit.

[DOK-L2; *explain*; DOK-L1; *summarize*]

Slide 26: Lift is a complicated phenomenon that doesn't lend itself to a simple explanation. The flow around an airfoil is complex and involves us trying to visualize movements that aerospace engineers normally calculate with computers running complex math equations. But we do know that, at subsonic speeds, it is a combination of Bernoulli's Principle and Newton's Third Law.

EVALUATE

Teacher Material: Theories of Lift Presentation

Slide 27-28: Before conducting the summative assessment, review the private pilot test question with students.

Slide 29: Conduct the **Summative Assessment.** Have students use their knowledge of how lift works to create a script and storyboard for a YouTube video that teaches viewers why the each of the three incorrect theories of lift are in error.

Summative Assessment

Have students use their knowledge of how lift works to create a script and storyboard for a YouTube video that teaches viewers why the each of the three incorrect theories of lift are in error.

Goal: To educate new pilots about the incorrect theories of lift

Role: You are a flight instructor in a collegiate flight school program

Audience: The target audience is student pilots

Situation: To prepare the new student pilots for the rigorous flight training program at your college, you need to help them understand how lift really works. There has been a lot of misinformation spread over the years that uses the incorrect theories of lift to train new pilots.

Product Performance and Purpose: You need to create the storyboard and script for a YouTube video that will be used to train all new student pilots in your college's flight training program. Using your knowledge of how lift is actually generated, you need to teach them why the three most common incorrect theories of lift (equal transit time, skipping stone, and Venturi) are in error.

[DOK-L4; *create*; DOK-L2; *explain*]

Summative Assessment Scoring Rubric

- Follows assignment instructions
- Written explanation includes:
  - Clear organization of ideas
  - Correct grammar and spelling
  - Explanations are clear and appropriate for a non-aviation audience
  - Accurate explanations of how each of the 3 incorrect theories are in error (Equal Transit /Longer Path, Skipping Stone, Venturi)
- Contributions show in-depth thinking including analysis or synthesis of lesson objectives
- Storyboard includes:
  - Drawings or pictures that accurately depict the associated script section (e.g., two molecules splitting at the leading edge of an airfoil and meeting at the trailing edge to depict "equal transit" theory)

- A clear logical order in how the pictures are organized

Points	Performance Levels
9-10	Consistently demonstrates criteria
7-8	Usually demonstrates criteria
5-6	Sometimes demonstrates criteria
0-4	Rarely to never demonstrates criteria

GOING FURTHER

If time and interest allow, have the students create actual videos from their story boards and YouTube scripts.

STANDARDS ALIGNMENT

NGSS STANDARDS

Three-dimensional Learning

- **HS-PS2** Motion and Stability: Forces and Interactions.
- **HS-PS2-4.** Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.
- **HS-PS2-6.** Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.
  - **Science and Engineering Practices**
    - **Analyzing and Interpreting Data** Analyze data using tools, technologies, and/or models (e.g., computational, mathematical) in order to make valid and reliable scientific claims or determine an optimal design solution.
    - **Obtaining, Evaluating, and Communicating Information** Communicate scientific and technical information (e.g., about the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically).
  - **Disciplinary Core Ideas**
    - PS2.B1: Types of Interactions Newton's law of universal gravitation and Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects.
  - **Crosscutting Concepts**
    - Cause and Effect Empirical evidence is required to differentiate between cause and correlation and make claims about specific causes and effects.
- **HS-ETS1-2** Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

COMMON CORE STATE STANDARDS

- **RST.11-12.1** - Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the authors makes and to any gaps or inconsistencies in the account.
- **RST.11-12.12.7** - Integrate and evaluate multiple sources of information presented in diverse formats and media (e.g., quantitative data, video, multimedia) in order to address or solve a problem.
- **WHST.11-12.2** - Write informative/explanatory texts, including the narration of historical events, scientific procedures /experiments, or technical processes.
- **MP.4** - Model with mathematics. (HS-ETS1-2)
- **HSN.Q.A.3** - Choose a level of accuracy appropriate to limitations on measurement when reporting quantities.

REFERENCES

https://www.aopa.org/-/media/Files/AOPA/Home/Pilot%20Resources/Aviation%20Resources%20for%20Youth/Join%20AOPA%20on%20the%20PATH%20to%20Aviation/AOPAs%20PATH%20to%20Aviation/module4.pdf
https://www.grc.nasa.gov/www/K-12/airplane/short.html
https://www.grc.nasa.gov/www/K-12/airplane/wrong1.html
https://www.grc.nasa.gov/www/K-12/airplane/wrong2.html
https://www.grc.nasa.gov/www/K-12/airplane/wrong3.html
https://www.youtube.com/watch?v=fw_C_sbfyx8
https://www.youtube.com/watch?v=iMhdksPFhCM