In Thrust We Trust

Session Time: Three, 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 enables a pilot to fly the aircraft to its maximum capabilities in both normal and abnormal situations. (EU5)

ESSENTIAL QUESTIONS

1. Is a propeller-driven or jet engine better for producing thrust?
2. How can aerodynamic forces make flying an aircraft more complicated and challenging?

LEARNING GOALS

Students Will Know

- A propeller is a rotating airfoil that operates on the principle of Newton's Third Law
- Propellers can have adjustable blade angles to make them more efficient.
- There are 4 turning and/or yawing tendencies caused by the propeller
- Jet engines create thrust through Newton's Third Law

Students Will Be Able To

- *Analyze* how propellers create thrust. (DOK-L3)
- *Describe* the four turning tendencies caused by propellers. (DOK-L2)
- *Differentiate* between variable-pitch and fixed-pitch propellers. (DOK-L3)
- *Explain* how jet engines create thrust. (DOK-L2)

ASSESSMENT EVIDENCE

Warm-up
A vocabulary quiz show game will help refresh students' memories about important terms that will be used in this lesson.

Formative Assessment

Students will write a paragraph comparing and contrasting the advantages and disadvantages of a fixed-pitch versus a variable-pitch propeller.

Summative Assessment
Students will imagine they are an engineer for Sonex Aircraft and will create a technical briefing for an airplane that comes with either a jet or a propeller-driven engine. Students will list the pros and cons of each aircraft and provide an assessment of which type of thrust is safer and why.

LESSON PREPARATION

MATERIALS/RESOURCES

- In Thrust We Trust Presentation
- In Thrust We Trust Student Activity 1
- In Thrust We Trust Student Activity 2
- In Thrust We Trust Teacher Notes 1
- In Thrust We Trust Teacher Notes 2
- In Thrust We Trust Teaching Aid

As The Prop Turns Activity

- Rubber band-powered balsa wood airplane with wheels
- Recommendations - Guillow's Jet Stream (https://www.guillow.com/jetstream.aspx); Guillow's Balsa Wood Flying Machine Kit (https://amzn.to/2QrnHRo)

Gyroscopic Action Demonstration (Optional)

- Chair that swivels
- Bicycle wheel that students can grasp by the axle.

Engineering a Jet Engine Activity

- iPads with "Rolls-Royce Trent XWB" application downloaded (free) https://itunes.apple.com/us/app/rolls-royce-trent-xwb/id988798634?mt=8

Recommended Student Reading

- **Pilot's Handbook of Aeronautical Knowledge**
  Chapter Five, Section on Propeller Principles https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/07_phak_ch5.pdf

LESSON SUMMARY

Lesson 1: In Thrust We Trust

This three session lesson will begin with a review of airfoil-related terms that students have already learned. They will be using these terms throughout the lesson on propellers, since propellers are also airfoils.

A rubber band-powered balsa wood model airplane will serve as a handy demonstration of some simple propeller basics, such as the direction of spin. Students will then learn how propellers have an inherent variability in thrust production due to the difference in velocity from blade root to tip. Students will use the lift formula (which applies to thrust) to understand how velocity changes over the length of the blade and then use what they know about airfoil design to determine how to they can even out the stresses on the blade.. This will lead to a discussion of optimal blade angle for different stages of flight, and how the development of a constant-speed or variable-pitch propeller addressed the problems of fixed-pitch propellers.

On the second day, students will explore how rotating propellers create four turning tendencies. These phenomena are the Corkscrew Effect, Torque Reaction, P-Factor, and Gyroscopic Force. Every pilot must be knowledgeable about the basis for these effects, so that they can both predict and respond to these turning/yawing forces. At the end of the section on propellers, students will complete a formative assessment by writing a paragraph comparing fixed-pitch to variable-pitch propellers.

Finally, students will learn how jet engines produce thrust and compare that to propellers. Although they seem complicated, jet engines are based on simple physics principles that can be broken into five stages: intake, compression, combustion, turbine and exhaust.

As a summative assessment, students will imagine they are engineers for Sonex Aircraft and will create a technical briefing for an airplane that comes with either a jet or a propeller engine. Students will list the pros and cons of each aircraft and provide an assessment of which type of thrust is safer and why.

BACKGROUND

Understanding propulsion -- the production of thrust -- is an essential part of both designing and flying aircraft. Modern aircraft are typically driven by either propellers or jet engines. Like airplane wings, propellers are airfoils. They produce thrust using the same principles by which a wing produces lift. In fact, we can use the lift equation to make predictions about thrust production along the blade of a propeller, and to determine how best to minimize thrust variation along the blade. Thrust variation is reduced by adding a twist to the propeller blade, and varying the camber and size of the blade along its length.

In addition to producing thrust, turning propellers introduce four unwanted forces that must be corrected for. Three of these forces produce left turning tendencies, which pilots learn to compensate for using flight controls.

Jet engines were developed to get around the limitations of propellers. Instead of moving large amounts of air at low speeds as a propeller does, they move relatively small amounts of air at very high speeds. A jet engine has five stages: Intake, Compression, Combustion, Turbine, and Exhaust. Although the stages rely on simple physics, the high speed, temperature, and pressure put extreme demands on the engine components, especially the fan, compressor, and turbine blades. Designing and building jet engines that can effectively use materials and engineering techniques to overcome these stresses requires a great deal of knowledge and research, which is among the reasons only a handful of companies worldwide are capable of designing and manufacturing jet engines.

MISCONCEPTIONS

Students may think of propellers as simple fan blades, not realizing how much engineering goes into designing a propeller. Whereas fan blades often have a constant pitch and size along the length of the blade, propeller blades are twisted to provide varying pitch along the length of the blade, as well varying size. Like a wing, and unlike fan blades, propeller blades have camber to assist in producing thrust. Some propellers also have adjustable pitch and fans do not.

DIFFERENTIATION

To support student comprehension in the **EXPLORE** and **EXPLAIN** sections, provide a graphic organizer such as a Know /Want-to-Know/Learned (KWL) for students to complete regarding the information on the four forces of flight, airfoils, and Newton’s Third Law. This will allow students to better understand the structure of new information on propellers and thrust and also connect working and long-term memories.

LEARNING PLAN

ENGAGE

Teacher Materials: 10_IntroductionToFlight_4_D_1_InThrustWeTrust_Presentation
In Thrust We Trust Teaching Aid

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

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

Warm-Up

A vocabulary quiz show game will help refresh students' memories about important terms that will be used in this lesson.

Divide the class into two evenly-sized groups. Each group selects one student to be the "buzzer." This student will "buzz in" by raising their hand when the group knows the definition of a term.

Refer students to the "Aero Quiz Show" board on slide 5. Determine which team will select the first category and point value. The teacher should refer to **In Thrust We Trust Teaching Aid** to read the term associated with the chosen category and point value. Allow the teams to confer on the definition of the term before the "buzzer" raises their hand. The first group to buzz in provides a definition. If the definition is correct, that team has earned the points for that term.

If the definition is inadequate, the other team has a chance to confer and provide a better definition.

The first team that offers the correct definition wins the points and is allowed to choose the next term. Keep a running total of points earned for each team on the board. Once all the terms have been defined, the team with the most cumulative points is the winner.

Be sure to reiterate the correct definition clearly each time.

[DOK-L1; *define, recall*]

EXPLORE

Teacher Material: 10_IntroductionToFlight_4_D_1_InThrustWeTrust_Presentation

Slide 6: Ask students to recall the four forces of flight:

- Lift is what pulls an airplane into the sky. Created by wings on an airplane, or the rotor blades of a helicopter or drone, it, by definition, acts perpendicular to the relative wind or the line of flight.
- Weight is the force of two masses being attracted to each other. It is the force that pulls objects towards the center of the earth, and makes things fall down.
- Thrust is created by the jet engines or propellers of an airplane. Thrust is the push that moves an aircraft through the air.
- Drag is the resistance (or friction) to things moving through the air. It is caused by air particles bumping into the object.

Associate the lift that wings produce with the thrust that propeller blades produce through the power of an engine. In the lift section of this unit, students learned that propellers are rotating airfoils rotating in the vertical plane. Examining a propeller blade will reveal that, like an aircraft wing, the blade is curved on one side. Curvature on the forward side of the blade, along with the twist of the blade, provides thrust just like camber and angle of attack of the wing provide lift. But because of the placement of the propeller and the design of its blades, the "lift" it creates is horizontal and moves the airplane forward rather than up.

Ensure students understand that thrust is essentially "lift" being created in the direction of flight.

Slide 7: This lesson will reintroduce how propellers are airfoils that act in a horizontal direction to create thrust. Review the parts of an airfoil in preparation for examining the propeller:

- Leading edge - the first place air makes contact with the airfoil.
- Trailing edge - the last place air makes contact with the airfoil. This is the back edge of the wing (or propeller blade).
- Chord - an imaginary straight line connecting the leading and trailing edges of an airfoil.
- Relative wind - the direction of airflow relative to the wing when the wing is moving through the air. Relative wind always moves directly opposite the direction the aircraft is moving.
- Angle of attack - angle between the chord line and direction of the relative wind.
- Thickness - the point where the airfoil has the greatest height from top to bottom; expressed as a fraction or percentage of the chord.
- Camber - curvature of the airfoil and may be considered curvature of the mean camber line.
- Mean camber - a line drawn between the leading edge and trailing edge so that the distance between the upper and lower surfaces of the airfoil is equal.
- Maximum camber - the point on the airfoil with the greatest distance between the mean camber line and the chord line; the location of the maximum camber helps define the shape of the mean camber line.

Slide 8: A propeller is a rotating airfoil that produces thrust by its action on the air in a direction perpendicular to its plane of rotation.

Use the diagram to point out the similarities between the design of a wing airfoil and the design of a propeller blade. Refer back to the diagram on the previous slide for clarification. Both propellers and wings are engineered with focus on the leading and trailing edges, chord line, angle of attack, thickness, and camber.

Slide 9: Ask students to recall Newton's Third Law: For every action, there is an equal and opposite reaction.

For propellers, define the action and its equal and opposite reaction.

Action: The rotating propeller blades move a large mass of air toward the rear of the aircraft.
Reaction: An equal and opposite movement of the airplane forward.

The "reaction" to the "action" of the rotating propeller blades is production of thrust.

Slide 10: This short video will help students to visualize how the propeller "screws into" the air and "captures" or "takes a bite" out of the air.

- "The Propeller Explained" (Length 1:39)
  http://video.link/w/bvse

Slide 11: This activity helps students visualize propeller action using a simple rubber band-powered balsa wood airplane. Divide the class into small groups based on the number of model airplanes available. Clear space on the floor for them to test propeller propulsion on the floor (without actually flying the airplanes). Provide each student with **In Thrust We Trust Student Activity 1** and direct students to answer the questions and record their observations for the first part only (the second part will be completed later in the lesson). Step-by-step instructions and possible answers are provided in **In Thrust We Trust Teacher Notes 1.**

This activity will likely conclude the first session. If time allows, complete the following 3-2-1 assessment.

Teaching Tips

Working individually, have students write the following on a piece of paper:

- List 3 things you didn't know before about propellers
- List 2 things that surprised you about propellers
- List 1 question you have about propellers

Slide 12: This slide illustrates what appears to be a paradox: the sections of a propeller blade all move together, but at different velocities! Use the diagram to show how the tips of the blade have a greater distance to travel than the sections near the center.

Speed equals distance divided by time. Since the entire blade completes a revolution in the same amount of time, but each part of the blade covers a different distance, the speed the blade is moving varies along the length of the blade, The tips, covering more distance, are moving faster than the roots, covering a smaller distance.

Teaching Tips

Students may be unfamiliar with the term "velocity." Provide a definition as needed. Velocity is the rate of speed at which something moves in a given direction.

Slide 13: Students will have a better understanding of propeller velocity by using the following demonstration.

Ask five students to stand in a straight line, shoulder to shoulder. The student at one end is the root of the propeller, while the student at the other end is the propeller tip. Then, direct the students to start walking by rotating around a center point next to the student at the root, staying in a straight line. The student at the tip will have to walk more quickly to keep in line than the one at the root if they are to stay in line with each other.

For an added bonus, have them speed up! It will be tricky for the student at the tip to keep up. Ask students to imagine the pressure on the blade tip at high speeds.

Slide 14: Ask students to consider the consequences of the differences in velocity along a propeller blade, based on what they just learned. As a hint, tell students to consider the lift equation. The next slide will provide the answer and cover the concept in greater detail.

Questions

Possible answer: *Students should recall the elements of the lift equation and conclude that variable velocities along the length of the propeller blade would create asymmetric thrust (lift). Varying* *velocity along the propeller would cause too little thrust at the root and too much thrust at the tip. This would put tremendous pressure on the tip, distorting the blade and potentially bending or breaking it.*

Slide 15: Remind students that lift is proportional to velocity squared and the coefficient of lift (CL), which increases with increasing angle of attack.

Remind students that propellers are airfoils, and airfoils produce lift, so we can use the lift formula here. However, be sure they remember that the propeller's lift is produced in a forward direction, so it is called thrust.

Students should remember that velocity is the factor that most affects lift. Because velocity in the equation is squared, faster moving airfoils generate exponentially more lift.

Slide 16: The point of this exercise is to demonstrate how quickly variable velocity along a constant angle of attack propeller blade will cause thrust to build towards the tip of a propeller. If the coefficient of lift, density and surface area are held constant, just square the velocity (in any units) to determine the relative values.

Have students draw a freehand graph with three units on the X axis labeled 10, 20, and 30, representing the number of inches measured from the hub of the propeller. On the Y axis, have students create 10 divisions, which will be labeled once they have calculated the values for relative lift at 10, 20 and 30 inches. [158,404 / 10 = 15.8 units of Relative Lift (aka: thrust) per division]

Blade Position	Velocity	Relative Lift
10"	129 kts	*16,641*
20"	259 kts	*67,081*
30"	398 kts	*158,404*

Slide 17: The students' graphs should resemble what is shown on this slide, indicating exponentially more thrust at the tip, due to the greater velocity, than near the root where velocity is slower.

Questions

Ask students if they think an engineer would design a propeller that would produce this kind of thrust distribution. Why or why not?

They should answer no. The tip of this propeller would be producing too much thrust, creating extreme forces on the blade, which would likely lead to blade failure.

Slide 18: Students should now understand that each part of the propeller blade must be different in order to create even thrust across the entire airfoil.

Have students brainstorm solutions to creating symmetric, or even, thrust from root to tip. Using what they know from the lift formula, ask students what factors could be varied in order to evenly distribute the thrust produced along the length of a propeller blade. Students may need to be reminded that changing the camber and angle of attack changes the coefficient of lift. The following slide will provide a detailed answer to this question.

Questions

Possible responses may include:

- Change the angle of attack so that is greater where the velocity is slow (more lift) and shallower where the velocity is high (less lift).
- Increase the camber at the root (more lift) and and decrease it at the tips (less lift).
- Change the surface area of the propeller (less area at the tips and more at the root).

Teaching Tips

Consider using a Think-Pair-Share approach for this question. First, each individual student should think about their response to the question. Then, divide the class into pairs. Each pair of students should discuss their answers to the question, before sharing out with the entire class.

Slide 19: Present the three possible variables that can be manipulated by engineers to create even thrust along the length of a propeller blade:

- Change the angle of attack - One solution for an engineer is to change the angle of attack along the propeller blade by twisting it, so that the angle of attack is higher where velocity is slow (to induce more lift) at the root and the attack of attack is lower where the velocity is high (to induce less lift) at the tips.
- Change the camber - An engineer may also tweak the camber, giving it more curvature at the root so that it induces more lift, and reduce the curvature at the tip so that less lift is produced.
- Change the surface area - An engineer may also adjust the surface area, decreasing the area at the tip and increasing the area at the root.

Slide 20: Use the diagram and a photo to show how engineers have solved the symmetrical thrust problem with blade twist, camber, and surface area. Show how the angle of attack, camber and surface area are varied along the length of a propeller blade.

Teaching Tips

If possible, use a model propeller to show the blade twist.

Slide 21: The blade of a propeller, just like a wing, has an angle of attack (AOA). Since a propeller is rotating as well as moving forward with the aircraft, its angle of attack is a combination of the two motions. Because of the speed of the forward motion changes depending on what the aircraft is doing, the angle of attack is also changing. That means that it not possible for a propeller whose pitch can't be changed (fixed-pitch) to always be at the most efficient angle of attack. A propeller with a pitch that would be efficient when the aircraft is climbing would not be efficient when the aircraft is in cruise.

The propeller in this situation is analogous to a single-speed bicycle. While a single-speed bicycle may work well on level ground, it may not be the best tool for climbing hills. When going down a hill on a single-speed bike, it may not be possible to pedal fast enough to provide any power.

It's the same for a propeller. When in a climb, a propeller will perform well in "low gear," able to turn faster and deliver more power. This would equate to a low, or small pitch on the propeller. Once the aircraft is in cruise, the propeller would perform better in a "high gear," or with a larger pitch.

> **Teaching Tips**
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> To continue the bicycle analogy, compare the gears of a bicycle to the angle of attack on a propeller blade. Ask students to recall or share what is like to use a multi-gear bicycle.
>
> A bicycle rider may use a larger-sized low gear to start moving from a stop. This puts less stress on the cranks and reduces the amount of effort the rider uses to get moving.This is analogous to a propeller blade with a lower pitch (angle of attack).
>
> Once moving, the bicycle rider may shift to a smaller-sized high gear, so that each turn of the pedal produces more forward thrust. This is analogous to a propeller blade with a higher pitch.

Slide 22: Fixed-pitch propellers with a low pitch are designed to be optimal for taking off and climbing. This type of propeller is know as a "climb propeller." At the lower pitch, the propeller handles a smaller amount of air for each revolution. Handling less air allows the engine to turn at a higher RPM. The high RPM creates maximum thrust.

However, once the airplane is cruising, the propeller spins too quickly and is not able to push enough air during each revolution.

Slide 23: Fixed-pitch propellers with a high pitch are designed to be optimal for cruising. This type of propeller is known as a "cruise propeller." At a higher blade angle, the propeller handles more air on each revolution, which causes the engine to turn at a lower RPM. Decreasing the engine RPM reduces fuel consumption and engine wear, while still keeping thrust at a maximum.

During takeoff and climb, an engine using a cruise propeller must work harder as it tries to rotate and produce enough thrust with such a high pitch.

There are also "all-purpose props" that are a compromise between these extremes.

Slide 24: Variable-pitch propellers allow pilots to change the blade angle to maintain the most efficient AOA. They allow a single propeller to operate with the efficiencies of a climb or cruise propeller, but at the price of increased cost and complexity. Most trainer aircraft have fixed-pitch propellers because of the increased cost and complexity that comes with variable-pitch propellers.

A constant-speed propeller is the most common type of variable-pitch propeller.

The constant-speed propeller can be thought of as an automatic variable-pitch propeller, because the pilot selects the desired rpm and the propeller automatically adjusts the blade angle to maintain that rpm. Students should understand that the blade angle will be smaller when climbing than when in cruise flight. The pilot sets a low pitch (high rpm) for takeoff, and a higher pitch (low rpm) for cruise, using a propeller control knob or lever next the throttle.

> **Teaching Tips**
>
> Pause here to have a brief discussion about why maximum thrust is seldom desirable. For cruise, a long-range cruise angle of attack (AOA) resulting from a set pitch and power setting ensures the best range for aerodynamic efficiency and fuel conservation purposes. Even during takeoff and climbout, takeoff rated thrust (which is still short of maximum) is only recommended for a minimal

amount of time until obstacles are cleared or the required climb gradient is met. Max thrust puts a massive strain on the engine(s) (shown as red line RPMs), causing damage and potential failure, and should only be considered for crash avoidance—for instance, when losing one or more engines at low altitude or heavy weight.

Slide 25: Complete the **Formative Assessment.** This will complete the second session.

Formative Assessment

Ask students to write and submit a paragraph that provides the following information:.

- Compare and contrast the advantages and disadvantages of a fixed-pitch versus a variable-pitch propeller. In your response, be sure to mention efficiency, cruise propeller, climb propeller, cost and complexity.

  Sample student response: A fixed-pitch propeller can only be most efficient at one airspeed, whereas a variable-pitch propeller can be adjusted so as to be efficient at different airspeeds. For an airplane with a fixed-pitch propeller to get the best climb performance, it would have to have a climb propeller with a low pitch, which would deliver high RPM, but at the cost of cruise performance. Conversely, to optimize for the best cruise speed would require a cruise propeller with a higher pitch, which would sacrifice climb performance. Despite these limitations, many aircraft, especially training aircraft, have fixed-pitch propellers because they are less expensive and complex.

[DOK-L2; Compare and Contrast]

EXPLAIN

Teacher Materials: 10_IntroductionToFlight_4_D_1_InThrustWeTrust_Presentation
, In Thrust We Trust Teacher Notes 1

Student Material: In Thrust We Trust Student Activity 1

Slide 26: If a simulator is available, the teacher may want to introduce left turning tendencies by doing a quick simulator demonstration. Simply set the airplane up on the runway with the engine running. Apply full throttle without applying any right rudder correction. The students will see the airplane veer to the left and off the runway.

Although the propeller creates the thrust that makes airplanes what they are, it also creates several unwanted effects that pilots must learn to recognize and correct. There are four different forces at work that cause an airplane to turn or twist around its axis as a result of the propeller producing thrust. They are commonly referred to as the four left-turning tendencies, because they all can cause either the nose of the aircraft or the wings to rotate left. Although they create the same result, each force works in a unique way.

- Corkscrew effect - also known as a spiraling slipstream
- Torque reaction - a reactive force
- P-factor - also known as asymmetric propeller loading

- Gyroscopic action - which can also cause turns to the right

Emphasize for students that a pilot MUST expect these forces and understand how to correct them to maintain a flight path.

Show students this video that explains each tendency.

- “The Four Types of Left Turning Tendencies” (Length: 5:03)
  http://video.link/w/vHpe

Slide 27: Note for students how Newton’s Third Law becomes relevant yet again in explaining the Corkscrew Effect, also known as spiraling slipstream. The corkscrew effect is especially pronounced during climbout.

Use a model airplane to demonstrate the mechanics behind spiraling slipstream: air spirals in a clockwise direction around the fuselage; the slipstream strikes the vertical stabilizer on the left side (action), pushing the tail to the right (reaction); as a result, it pushes the nose to the left.

The slipstream is strongest when the propeller is producing high thrust at low airspeeds, as with takeoff and climb.

This video shows the slipstream force and the resultant yaw to the left in reaction to the pressure on the tail. Ask students to watch carefully to see if they can see the rain spiraling around the airplane during takeoff revealing the spiraling slipstream. You might replay the video a second time for students.

- “Crop Duster with Spiraling Slipstream Visual Effect” (Length 0:25)
  http://video.link/w/rNje

Slide 28: Torque reaction is another example of Newton’s Third Law at work. When airborne, an aircraft’s engine parts and propeller rotate in a clockwise direction (action), which forces the aircraft itself to rotate in a counterclockwise direction (reaction). This tends to make the aircraft roll to the left.

In the United States, airplane propellers turn clockwise (as seen from inside the cockpit). But in some foreign countries, propellers turn counterclockwise. Ask students how torque would affect an airplane with a propeller that spins counterclockwise. They should realize that it would create a right-turning tendency.

Explain to students that torque reaction is especially prominent at low speeds with high power settings. At higher speeds, the aerodynamic forces from the airflow over the airplane’s control surfaces lessen the torque effect. At lower power settings, the propeller is not spinning as quickly and therefore the torque effect is reduced.

Slide 29: Using the balsa wood airplanes from the previous activity for a demonstration showing torque effect. Direct students to the second part of **In Thrust We Trust Student Activity 1**. Refer to **In Thrust We Trust Teacher Notes 1** for guidance and answers to the questions.

Slide 30: P-factor is caused by unequal thrust generated by the propeller blades. In a nose-up situation (higher angle of attack) on takeoff, when the power is maximized but speed is still building, the up-moving blade on the left (as seen by the pilot) has a lower angle of attack than the downward-moving blade on the right. Therefore, the blade on the right side of the airplane has more lift (known as thrust here) so it “pulls” the nose to the left.

Slide 31: Describe how gyroscopes work by explaining rigidity in space, in which a spinning wheel tends to maintain its orientation, or position in space. It’s a very useful property which serves as the basis for navigational instruments such as the attitude indicator, turn indicator and directional gyro (a mechanical compass).

Another property of gyroscopes is precession. Precession occurs when a force is exerted against the side of a gyroscope. The gyroscope reacts as if the force had been exerted 90 degrees in the direction of rotation around the wheel. This force is an unwanted byproduct of using a propeller for thrust and must be countered by the pilot using the aircraft’s flight controls.

Slide 32: When a force is applied to the tail of the aircraft to pitch the nose up or down, it’s equivalent to a force applied to the propeller. Since the propeller acts like a gyroscope, the force applied to it actually appears 90° off in the direction of rotation. Thus, pitching the nose up is like a force applied forward on the bottom of the propeller, which is rotating clockwise as seen from the cockpit, and the resulting force yaws the aircraft right.

To summarize, gyroscopic action is the result of a deflective force applied to a rotating body (propeller). The resultant action occurs 90° in the direction of rotation:

- Only occurs during pitch changes
- Pitching the airplane's nose upward causes a right-turning tendency
- Pitching the airplane's nose downward causes a left-turning tendency

This video shows how gyroscopic precession can be seen even in a simple model. The angular momentum of the propeller creates a yawing moment.

- "Gyro Effects on Aircraft Dynamics" (Length 3:05)
  http://video.link/w/K8qe

Teaching Tips

If time allows, give students the opportunity to experience the surprising strength of gyroscopic action, particularly precession.

For this demonstration, teachers will need a bicycle wheel that students can grasp by the axle. While not necessary, a a purpose-built bicycle wheel gyroscope with handles will also work for this demonstration (SEOH Bicycle Wheel Gyroscope).

- Invite a student to volunteer.
- Hand the bicycle wheel to the student and have them grasp the axle on each side of the wheel. Get the wheel spinning quickly.
- Have the student tilt the wheel from side-to-side. They should find feel that the bicycle wheel will tend to remain in its vertical orientation and that its takes strength to tilt it from side-to-side. But when a strong enough force is applied to tilt the wheel, the students will really feel it pull it off center.

If a chair that swivels very easily (with little friction) is available, ask the students to try sitting down and tilting the wheel while it is spinning. They should find that they can drive the rotation of themselves and the chair simply by tilting the wheel.

EXTEND

Teacher Materials: 10_IntroductionToFlight_4_D_1_InThrustWeTrust_Presentation
, 10_IntroductionToFlight_4_D_1_InThrustWeTrust_TeacherNotes2

Student Material: 10_IntroductionToFlight_4_D_1_InThrustWeTrust_StudentActivity2

Slide 33: Present the jet engine diagram and explain that students will begin by reviewing the five stages of the jet engine: intake, compression, combustion, turbine rotation, and exhaust. The jet engine can be reduced to these five simple stages.

- Air enters the engine at the intake through suction created by the engine itself.
- This air then passes through a compressor. The compressor section is made up of several stages, each with a set of blades rotating at very high speed. Each stage of the compressor increases the pressure of the air.
- Combustion takes place Inside the combustor where the air is injected with fuel and ignited, creating a contained explosion. Due to the energy released at ignition, the air is pushed through a turbine component and then through the exhaust.
- The turbine component is a series of fans with rotating blades, similar to the compressor section. The high-energy air forces the turbine blades to rotate. A shaft connects the turbine and compressor sections, allowing the turbine to drive the compressor section.
- Next, the high-energy air leaves the engine through the exhaust at high speed. The air moving rearward at high speed propels the engine (and attached aircraft) forward due to Newton's Third Law.

Show students the following video to support this explanation.

- "How Jet Engines Work" (Length: 2:19)
  http://video.link/w/dule

Slide 34: Explain the similarities and differences between propellers and jet engines.

Both jet engines and reciprocating engines convert thermal energy in the form of combusted fuel into thrust. Although jet engines seem more complicated, they perform the task of generating thrust more simply since the thrust comes directly from the engine. A propeller driven by a piston engine is using the combusted fuel to drive pistons back and forth, which turn a crankshaft, which is connected to a propeller, introducing complexities and inefficiencies at each stage.

One of the major limitations of a propeller is its size. A propeller works by accelerating a relatively large volume of air to a slow velocity. To develop more thrust, it must move more air, requiring a larger propeller, with tips that are moving faster as the size of the propeller grows. As the tips of the propeller approach the speed of sound, the propeller's efficiency is destroyed and a limit of size and thrust is reached.

A jet overcomes many of the limitations of a propeller by accelerating a relatively small volume of air to a high velocity. A jet can produce much more thrust, at higher altitude, and at greater speeds. Jet engines run smoothly and produce high power for their weight.

Propellers do have advantages. They can produce most of their total available power at the start of a takeoff roll and respond quicker to movements of the power lever than jets.

Slide 35: Explain that the jet engine shown is a "turbojet," because it has a turbine driving a fast jet of air. All of the thrust is coming from hot exhaust gasses. The main advantage it has over a propeller is the potential for higher thrust and aircraft speeds.

However, the turbojet's initial thrust is relatively low and it suffers from poor fuel efficiency. This led to the development of the turbofan, which combines the advantages of a propeller and jet.

Slide 36: A turbojet and a turbofan operate on the same principles, the difference being that a turbofan engine drives a much larger inlet fan, which produces a large percentage of the thrust that the engine is delivering. Much of the additional air going through the fan isn't taken into the engine itself to be combusted, but flows outside the core of the engine. This is called "bypass air," since it is bypassing the interior of the engine. Students should see that the fan is treating the bypass air much as a propeller would, thus delivering some of the advantages of a propeller, such as available thrust at low speed and greater fuel efficiency, to a jet engine. These advantages lead to better acceleration, a shorter takeoff roll, and improved climb performance.

Slide 37: In this activity, students will watch a video and use an app to explore the stages of a jet engine. Divide the class into small groups, depending on the number of devices available. Make sure they have access to the digital resources.

- Video: "Engineering Atoms" (Length: 6:46)
  http://video.link/w/Jdqe

- App: "Rolls-Royce Trent XWB" (free)
  https://itunes.apple.com/us/app/rolls-royce-trent-xwb/id988798634?mt=8

Distribute a copy of **In Thrust We Trust Student Activity 2** to each student. Direct them to follow the procedure and answer the questions. Possible answers for the questions are provided in **In Thrust We Trust Teacher Notes 2.**

EVALUATE

Teacher Material: 10_IntroductionToFlight_4_D_1_InThrustWeTrust_Presentation

Slides 38-43: Quiz students on questions related to turning tendencies for the Private Pilot Knowledge Test.

Slide 44: Conduct the **Summative Assessment.**

Summative Assessment

Students will imagine they are engineers for Sonex Aircraft. The company is close to FAA certification for their new airplane, which happens to come with an option for either a jet engine or a propeller-driven engine. The FAA requires the company to create a technical briefing for the two airplanes that lists the pros and cons of each aircraft based on the type of thrust each aircraft utilizes. The technical briefing must also include a professional assessment of which type of thrust is safer and why.

Students should submit at least two written paragraphs and a table of the pros and cons.

[DOK-L2; *Explain; DOK-L3; Develop a logical argument*]

Summative Assessment Scoring Rubric

- Follows assignment instructions
- Explanations show evidence of each of the following:
  - Accurate and complete list of the pros and cons of propeller and turbine engines
  - Thoughtful analysis of which type of engine is safer
  - Accurate and persuasive supporting evidence for the safety assessment
- Contributions show in-depth thinking including analysis or synthesis of lesson objectives
- Correct spelling and grammar

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

For understanding how propellers move air, try playing with a ceiling fan that can change direction. Many models are designed so that rotation in one direction blows air down, for cooling during the summer, while the other direction gently pulls air up to keep warm air circulating without chilling the inhabitants by blowing on them. Suggest that students go home and play with the direction of their ceiling fan until they can predict which way the air will move.

Students may be eager to give their balsa wood airplanes a proper test flight, but this cannot be done in the classroom, and may not fit into regular class time. Consider meeting interested students at lunch or after school to fly the airplanes in a large open space like the football field. Try to choose a time and place without strong winds -- and fly the airplanes after the necessary in-class activities are already completed! The delicate models may not survive their flights intact.

STANDARDS ALIGNMENT

NGSS STANDARDS

Three-dimensional Learning

- **HS-PS2-4 -** Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law describe and predict the gravitational and electrostatic forces between objects.
    - **Science and Engineering Practices**
        - Analyzing and Interpreting Data
        - Using Mathematics and Computational Thinking
        - Obtaining, Evaluating, and Communicating Information
    - **Disciplinary Core Ideas**
        - PS2.A Forces and Motion
        - PS2.B Types of Interactions
    - **Crosscutting Concepts**
        - Cause and Effect

COMMON CORE STATE STANDARDS

- **RST.9-10.2 -** Determine the central ideas or conclusions of a text; trace the text's explanation or depiction of a complex process, phenomenon, or concept; provide an accurate summary of the text.
- **RST.9-10.4 -** Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 9-10 texts and topics.
- **WHST.9-10.6 -** Use technology, including the Internet, to produce, publish, and update individual or shared writing products, taking advantage of technology's capacity to link to other information and to display information flexibly and dynamically.
- **WHST.9-10.8 -** Gather relevant information from multiple authoritative print and digital sources, using advanced searches effectively; assess the usefulness of each source in answering the research question; integrate information

into the text selectively to maintain the flow of ideas, avoiding plagiarism and following a standard format for citation.

- **WHST.9-10.9 -** Draw evidence from informational texts to support analysis, reflection, and research.
- **MP.4 -** Model with mathematics
- **HSNQ.A.2 -** Define appropriate quantities for the purpose of descriptive modeling

REFERENCES

https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/07_phak_ch5.pdf
https://www.grc.nasa.gov/www/k-12/UEET/StudentSite/engines.htm
http://www.boldmethod.com/learn-to-fly/aircraft-systems/how-a-constant-speed-prop-works/
http://hartzellprop.com/whats-the-difference-between-a-fixed-pitch-and-variable-pitch-propeller/