Gyroscopic Instruments

Session Time: Four, 50-Minute Sessions

DESIRED RESULTS

ESSENTIAL UNDERSTANDINGS

Safe and efficient aviation operations require that pilots use math, science, and technology. (EU3)

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. (EU4)

ESSENTIAL QUESTIONS

1. What characteristics of gyroscopes make them valuable for use in flight instrumentation?
2. What are the associated limitations?

LEARNING GOALS

Students Will Know

- The principle of rigidity in space
- The principle of precession
- Which instruments use gyroscopes
- How gyroscopic instruments are powered
- How to identify and respond to instrument failures

Students Will Be Able To

- *Analyze* images of heading indicators to determine the airplane's orientation. (DOK-L4)
- *Compare* the different types of gyroscopic instruments, including how they're mounted and the flight attitude information they provide. (DOK-L3)
- *Construct* a simple gyroscope and explain its properties in terms of what they know about airfoils, air pressure, and gyroscopes. (DOK-L3)

ASSESSMENT EVIDENCE

Warm-up
Students will watch a video about gyroscopes and discuss why gyroscopes behave as they do.

Formative Assessment
Students will read and analyze four different attitude indicator displays.

Summative Assessment
Students will demonstrate their depth of knowledge about gyroscopic instruments by answering a series of questions on topics including which instruments are gyroscopic, how are they powered, causes of failure, indications of failure, and correct responses to failure.

LESSON PREPARATION

MATERIALS/RESOURCES

- Gyroscopic Instruments Presentation
- Gyroscopic Instruments Student Activity 1
- Gyroscopic Instruments Student Activity 2
- Gyroscopic Instruments Student Activity 3
- Gyroscopic Instruments Student Activity 4
- Gyroscopic Instruments Teacher Notes 1
- Gyroscopic Instruments Teacher Notes 2
- Gyroscopic Instruments Teacher Notes 3
- Gyroscopic Instruments Teacher Notes 4

Make a Bottle Gyroscope (per student or group)

- 2 plastic soda bottles (1–2 liters) with smooth sides
- Sharp knife or scissors for cutting the bottle
- Cutting surface
- Electrical tape
- Ruler
- Safety glasses

Flight Simulation Activity (per pair)

- Flight simulator capable of simulating failures of gyroscopic instruments
- Stopwatch

LESSON SUMMARY

Lesson 1 - Gyroscopic Instruments
Lesson 2 - The Magnetic Compass

Students will warm up by watching a video demonstration of the behavior of gyroscopes. Students will then be asked to speculate on why gyroscopes remain upright while spinning, why they wobble and fall as their spinning wheel loses speed, and what childhood toys resemble a gyroscope.

During the next part of the lesson, students will be introduced to the gyroscopic flight instruments used in aircraft, with a focus on the physical principles that underlie gyroscopic behavior: rigidity in space and gyroscopic precession. Since gyroscopes must spin to be effective, students will also learn the sources of power that provide the spinning force. Students will complete an activity in which they construct a simple gyroscope from a plastic bottle.

Students will then learn about each gyroscopic instrumentthe attitude indicator, turn coordinator or turn and slip indicator, and heading indicatorincluding each instrument's basic function and its practical uses in flight. Students will also learn about the inclinometer, though this instrument is not itself driven by gyroscopes. Finally, students will learn about gyroscopic instrument failures, including how to recognize and to respond to particular failures. Students will have the opportunity to apply what they have learned in a flight simulator.

Students will answer questions from the FAA Private Pilot Knowledge Test and complete a summative assessment.

BACKGROUND

Airplanes operate in three dimensions and rotate about three axes, with flight controls for pitch, yaw, and roll. The orientation of each of those three axes is collectively known as the attitude of the aircraft.

Controlling the three axes of flight is relatively easy when the pilot can maintain visual contact with the horizon, but becomes impossible without additional instruments when vision is obscured by clouds or other weather.

Early aviation suffered many accidents due to *spatial disorientation*. Pilots who found themselves in weather that prevented an outside visual reference would attempt to rely on internal sensations and end up losing control of the aircraft. Instruments that provided an attitude reference were needed.

In addition to an attitude reference, pilots needed a stable way to maintain heading. Although a magnetic compass is reliable in the sense that there is little to go wrong, it is unstable and fails to indicate the correct heading when the aircraft is accelerating, decelerating, or in a turn. Such problems are manageable when the pilot can see something outside to steer the aircraft to, but when in the clouds the behaviors of the magnetic compass impede aircraft control.

It became apparent in the early 1900s that something had to be done to assist pilots in avoiding spatial disorientation, maintaining directional control with little or no visual reference points. In 1913, the first application of gyroscopes was introduced into airplane instruments. These instruments soon made it possible for trained pilots to fly in clouds and conditions of reduced visibility with much greater safety. Today, virtually all aircraft are equipped with at least one or two gyroscopic instruments, making them more capable, useful, and safe.

MISCONCEPTIONS

A common misconception is that our internal sense of up and down is always accurate; that is, we "just know" when our bodies are tilted one way or the other or when we're right-side-up or upside-down. Early aviation pioneers thought the same thing, and many died after losing spatial orientation when flying through clouds or haze. In truth, our perceptions of physical orientation are the result of several physiological factors, most of which can be "tricked" into providing our brains with false information. Spinning in place or going on an exciting amusement park ride can create sensory inputs that cause our brains to analyze incoming data incorrectly. Vertigo is a common result, as is motion sickness. Pilots in training soon learn that, contrary to popular belief, they *cannot* accurately judge their physical orientation through non-visual perceptions. In other words, the balance system of the body is ineffective when not supported by sighta situation that can cause pilots to lose control of their airplane.

DIFFERENTIATION

To support student engagement and comprehension in the **EXPLORE** and **EXPLAIN** sections, create learning centers for students to rotate to in small groups to explore the lesson concepts, such as the Gyroscopic Behavior, Gyroscopic Principles and Major Gyro Instruments. Create task cards for each center to focus student learning and give opportunities for reflection.

To support student comprehension in the **ENGAGE** and **EVALUATION** sections, give students the opportunity to read real world accounts of gyroscopic instrument failure to learn about implications of failure and pilot correction. An example can be found here.

LEARNING PLAN

ENGAGE

Teacher Material: Gyroscopic Instruments Presentation

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

Slide 4: Conduct the **Warm-Up**.

Warm-Up

Students will watch the following video, then answer the following questions:

- "Gyroscope" (Length 2:33)
  https://video.link/w/zmvj

Ask students the following questions and write down their answers on the board:

- Why do you think the gyroscope remains upright while spinning on the table?
- What happens to the gyroscope when the spinning slows down?
- Can you think of a childhood toy that resembles and acts like a gyroscope?

After discussing their answers, students should watch the remainder of the video.

https://video.link/w/5Avj (Length 2:30)

Compare students' initial answers to the questions to the answers provided in the video.

- Why do you think the gyroscope remains upright while spinning on the table?
  The spinning gyro creates a force that resists a change and results in the gyro displaying rigidity in space. This rigidity causes the gyro to remain upright.
- What happens to the gyroscope when the spinning slows down?
  The gyro only stays upright while it's spinning. Once the spinning slows down or stops, the gyro falls over.
- Can you think of a childhood toy that resembles and acts like a gyroscope?
  A toy top is a perfect example of a gyroscope. When not spinning, the top just lays there, but when it is spun it remains upright for as long as it spins. When it slows down, it wobbles and eventually falls to the floor.

Teaching Tips

The functioning of gyroscopes may seem strange and counterintuitive to many students. This video may be students' first exposure to gyroscopes, so they may be unaware that gyroscopes are capable of doing the things they do, sparking questions. If students ask a lot of questions about gyroscopes and how and why they function, record these questions so that students can discuss and record their answers as they complete the lesson; you can then use these questions and answers as a review sheet.

EXPLORE

Teacher Materials: Gyroscopic Instruments Presentation, Gyroscopic Instruments Teacher Notes 1, Gyroscopic Instruments Teacher Notes 2
Student Materials: Gyroscopic Instruments Student Activity 1, Gyroscopic Instruments Student Activity 2

Slides 5-6: Students will begin by watching this video about a pilot who has become disoriented while flying. After watching, discuss what students think has happened to the pilot. Then, proceed to the next slide to explain.

- "178 Seconds to Live" (Length 2:06)
  http://video.link/w/ueUg

Questions

After watching the video, ask students the following questions:

- What has happened to the pilot in this video?
  The pilot in this video has become spatially disorientedunable to discern his attitude and make proper corrections. Although he has instruments, he has not been trained how to interpret them and is attempting to rely on his body's sensations to control the aircraft.

- Why has he become disoriented while flying?
  The human body evolved to accurately perceive its orientation in space under "normal" circumstances. Walking down the street or sitting in a chair with our eyes open, our sensory systems tell us if we're upright, facing straight ahead, or tilting one way or another. This ability to accurately perceive our location in space, however, changes dramatically when one or more of these sensory systems is disrupted or cut off from the others.

  When pilots fly through clouds or fog or in the dark, they cannot see the horizon in the distance or the ground below. It is impossible to maintain the same level of spatial awareness, and it is easy for pilots to get disoriented, sometimes losing control of the airplane.

Early in the history of aviation, it became clear that, when flying in clouds and fog or at night, pilots needed instruments in their airplane that would simulate what they couldn't see naturally. Flight instruments based on gyroscopesthose strange devices that behave in such unusual wayswould change the face of aviation forever, making commercial aviation possible and dramatically improving flight safety.

Teaching Tips

The situation the pilot in the video got himself into is known as a "graveyard spiral." It is a common outcome when pilots who are not trained how to fly using instruments find themselves unable to see the horizon. In a graveyard spiral, the aircraft has entered an angle of bank that the pilot has not detected. As the aircraft starts to descend, the pilot notices and tries to correct by pulling back on the yoke. Since the aircraft is in a turn, pulling back on the yoke doesn't raise the nose, it tightens the turn, leading to a steeper descent. If not corrected by leveling the wings, the aircraft will continue to spiral down until hitting the ground.

Slide 7: There are three primary gyroscopic instruments used in aircraft: the attitude indicator, the heading indicator, and the turn coordinator.

The attitude indicator shows the pilot whether the aircraft is wings level or banking left or right. It also displays whether the nose is level with the horizon or pitched down or up. This is the only instrument in the airplane that shows orientation information for both pitch and roll (bank). It serves as an artificial horizon.

The heading indicator displays directional information, showing the direction in which the aircraft is pointed.

The turn coordinator displays the rate at which the aircraft is turning, measured in degrees per second. This is useful when flying in clouds and conditions of reduced visibility, when aircraft controllers are expecting a standard rate of turn. Attached to the turn coordinator is a device called the inclinometer. This device measures the quality of the turn: that is, whether the tail of the aircraft remains in line with the nose throughout the turn.

These instruments will be discussed in greater detail in later slides. All three rely on one or both of the principles of gyroscopic behavior: rigidity in space and precession.

Slide 8: There are two main physical principles that make gyroscopes useful in aircraft instrumentation:

- Rigidity in space: the ability of the gyroscope to remain in the same orientation regardless of the position and movement of its base
- Precession: the manner in which the gyroscope deflects when acted upon by an outside force

Slide 9: To illustrate the principle of rigidity in space, have students watch this brief video:

- "Rigidity of Gyroscope" (Length 0:23)
  https://video.link/w/7ezj

As this video shows, as the base of the gyroscope is moved in any direction, the spinning wheel at the center of the gyroscope remains in a fixed (rigid) position, aligned with the wheel's axis of rotation. This is known as the principle of rigidity in space. The faster the wheel spins, the more stable the gyroscope is; this is why the gyroscope in the Warm-Up video began to wobble and eventually collapsed as the wheel slowed in its spin.

The gyroscope shown in this video has gimbal ring mounts that enable the base to move in any direction while the wheel remains in its original orientation.

Slide 10: The principle of precession may seem both mysterious and baffling. Actually, it is neither when one understands the physics behind it. Precession refers to the manner in which a gyroscope responds to a force applied to it, such as when gently pushing the spinning wheel with your finger.

When a force is applied to most objects, those objects deflect at the point where the force is applied, in the direction that the force was moving at the time it impacted the object. With gyroscopes however, the deflection does not occur at the point where the force is applied, but rather 90° from that point in the direction of the rotation. Consider the illustration in this slide. If you push your finger against the top of the spinning wheel, that wheel will not deflect at the top, but rather at the right side, as illustrated. If you were to push on the right side of the spinning wheel, the deflection would occur 90° from that point: i.e., at the bottom of the spinning wheel. The reasons for this have to do with the concepts of angular momentum and competing forces in rotating objects.

This video provides a deeper explanation:

- "Gyroscopic Precession" (Length 3:48)
  http://video.link/w/7IUg

Slide 11: The gyroscopes in aircraft flight instruments only work when they are turning, so something has to get them spinning. To be effective, gyroscopes must spin at very high speed: as rapidly as 15,000 RPM. Power can come from one of three sources:

1. a vacuum pump that pulls air through the instruments, causing them to spin

2. a positive pressure pump that pushes air through the instruments, spinning them to high RPM

3. an electric motor that connects to the individual gyros, causing them to spool up to the required speed.

It is important that these power sources remain functioning during flight. If they slow down or fail, the gyroscopic instruments will provide incorrect information or fail entirely. When gyroscopes slow down or stop altogether, rigidity in space also fails, rendering the instruments useless.

This video excerpt shows more information about the vacuum power system:

- "Vacuum Systems and Gyroscopic Principles" (Length 1:43)
  https://video.link/w/4Xzj

Slide 12: The majority of aircraft use air pressure to provide power to the gyroscopic instruments. These pressure systems can provide vacuum or positive pressure to the instruments. The main gyroscopic instruments that use pressure to spool up their gyros are the attitude indicator and the heading indicator.

With the vacuum system, a pump draws air from the outside to create a partial vacuum. While the air is being drawn in, it passes through the attitude indicator and heading indicator, impacting on vanes in those instruments and causing their gyroscopes to turn. This is the most common system in light general aviation aircraft.

Positive pressure systems work the same way, except the pump pushes air against the vanes rather than pulls on them. Whether the pressure is positive or negative, the gyros spin and provide the rigidity in space needed for the instruments to function properly.

It is imperative that the air passing through the gyros be clean so as not to deposit contaminants and cause friction in the system. To prevent contamination, a special filter is applied at the point where the air is brought into the system from the outside. This filter ensures that only clean air is used to power the gyros.

A gauge inside the cockpit displays the amount of vacuum being produced by the pump. Pilots use this gauge to confirm that the instruments are receiving enough vacuum to function properly. A low vacuum reading on this gauge can indicate imminent instrument failure.

The following video shows the operation of a vacuum pump that might be found in a general aviation aircraft.

- "How It Works: Vacuum Pump" (Length 0:58)
  http://video.link/w/ONUg

Slide 13: The other source used to power gyroscopes in aviation instruments is electricity. In electric instruments, the gyros are turned by small electric motors contained within the instrument housing itself. These motors are connected to the airplane's electrical system and get their power from the airplane's battery and alternator.

Using electricity to power gyroscopes provides redundancy to the instrument system. Since the gyroscopes for most instruments are powered by either vacuum or positive pressure, having an electrical gyroscope that will continue to work in the event of a vacuum or pressure failure provides an added level of safety.

Another advantage of an electrical gyroscope system is that it is not dependent on pumps, hoses, and tubes to feed pressure to the instruments. The internal electric motor requires no additional plumbing to provide power to the gyro. And since there is no air flowing over vanes, there is no risk of dirt or other material contaminating the gyro.

Electrical gyros are most commonly found in turn coordinators rather than in heading indicators or attitude indicators, which are normally vacuum or pressure driven. Pilots appreciate the redundancy in having both pressure-driven and electrically driven gyros in the cockpit. However, some aircraft, particularly those that fly at high altitudes, rely on electrically driven gyros exclusively because there is insufficient air at altitude to power vacuum or positive pressure instrument systems.

This slide will likely conclude the first session.

Slide 14: Briefly review gyroscopic behavior from the previous session:

- Attitude indicators use gyros to provide roll and pitch information in a single display. Attitude indicators were previously called *artificial horizons*, because of the similarity between the physical horizon and the face of the instrument. The modern term for the device, however, is *attitude indicator*, though both terms remain commonly used.
- The heading indicator shows the pilot the direction in which the aircraft is pointed. The old term for this instrument, *directional gyro*, is still in common use in some quarters.
- Turn indicators, including the turn coordinator and turn-and-slip indicator, display the rate and quality of a turn.
- Two important physical principles make gyroscopes useful in airplane attitude instruments.
    - The principle of rigidity in space enables the gyroscope to remain in its original position even when the stand or frame it is sitting on changes its orientation by turning or tilting.
    - The principle of precession dictates that the gyroscope will respond to pressure from an outside force by deflecting 90 degrees away from the point of force application, in the direction of the rotation.

Slide 15: Students will follow the instructions in **Gyroscopic Instruments Student Activity 1** to construct gyroscopes from plastic soda bottles; they will then fly their gyroscope and answer questions about its flight behavior. Depending on the availability of materials, students may work individually or in pairs. See **Gyroscopic Instruments Teacher Notes 1** for sample answers to the analysis questions, along with teaching tips for facilitating the activity.

Slide 16: The attitude indicator is the most important instrument in the cockpit of any airplane being operated in conditions of low or zero visibility. With this instrument, the pilot can determine both bank angle and pitch, two dimensions that must be closely controlled for safe flight.

- The long, horizontal, white line represents the horizon; it is physically attached to the gyroscope, so it remains in the same horizontal position throughout the flight. The schematic airplane or aircraft symbol represents the orientation of the airplane relative to the horizon.
- The blue area represents the sky, or the area above the horizon. The brown area represents the ground below the horizon.
- The horizontal white lines above and below the horizon indicate degrees of pitch up and down. Each line represents five degrees of pitch. The attitude indicator is the only instrument in the cockpit that provides both bank and pitch information in a single display.
- The white radial markings around the top represent the degrees of bank, indicated by the alignment of the arrow symbol with the angle of bank markings. The white horizontal markings represent degrees of pitch: that is, the up-and-down motion of the nose of the airplane.
- The attitude indicator operates on the principle of rigidity in space. The gyroscope to which the face of the attitude indicator is attached remains horizontal in all aircraft attitudes, providing the pilot with a simulated view of the outside horizon. Unlike some other instruments in the cockpit, the attitude indicator does not lag or delay its readings. The attitude of the aircraft is immediately and accurately displayed to the pilot.

Slide 17: The gyroscope in the attitude indicator is mounted on the horizontal plane, with gimbals for pitch and roll. The horizontal bar or wings of the schematic airplane is physically attached to the gyroscope, and should display a level attitude while on the ground and in level flight. This horizontal bar remains level with the horizon throughout flight, with the aircraft rotating around the gyroscope to display orientation information.

Pilots can control the setting of this horizontal bar or wings through a knob attached to the instrument. Pilots may set this bar so that, from their perspective, the horizon bar is level with the horizon line on the background. This accommodates pilots of different heights.

The wings or horizontal bar represent the actual attitude of the aircraft in flight. This representation will display changing bank and pitch information as the airplane moves through the air.

This video illustrates principles and operation of the attitude indicator:

- "Attitude indicator" (Length 4:35)
  http://video.link/w/mjVg

Slide 18: Complete the **Formative Assessment**.

Formative Assessment

Students are given four different attitude indicator displays, and will be asked to describe the attitude of the aircraft as it relates to each display, and to consider both the bank and pitch attitudes exhibited in each display. Students will then apply what they know about the other aircraft instruments to answer questions. Provide students with **Gyroscopic Instruments Student Activity 2** worksheet.

[DOK 3; *Analyze*]

EXPLAIN

Teacher Material: Gyroscopic Instruments Presentation

Slide 19: It is important for pilots to be able to determine both the direction and rate of turns. Most aircraft today are equipped with one of two types of turn indicator: the turn and slip indicator, or the turn coordinator. Both of these instruments are powered by gyroscopes that enable the display of turn direction and turn rate: that is, the number of degrees the aircraft is turning per second.

Slide 20: The placement and orientation of gyros within flight instruments determine their functionality. In the turn and slip indicator, the gyro is mounted in the vertical plane that corresponds to the aircraft's longitudinal axis. The manner in which the gyro is mounted within the instrument limits the way the gyro can deflect. As a result, the turn and slip indicator will not indicate changes in orientation involving pitch (the up-and-down motion of the nose of the aircraft); it is limited to measuring the direction and rate of a turn.

A spring within the instrument centers the needle on the face. During a turn, the gyro tilts to the left or right, and the resulting precession causes pressure to be exerted against that spring, pulling the needle a certain distance left or right to indicate both direction and turn rate. The greater the precession, the greater the pressure exerted on the spring, and the more the needle moves.

Slide 21: The turn and slip indicator is both a direction and rate instrument. It shows the direction of turn, as well as how fast the aircraft is turning.

When the needle on the face leans left, that indicates a left turn; when the needle leans right, a right turn is indicated. When the needle deflects left or right and aligns with the pentagon ("doghouse") on the corresponding side, a standard rate turn is indicated. Standard rate is three degrees of turn per second. If the needle deflects halfway to the doghouse, a turn of 1–2 degrees per second is indicated.

Mounted at the bottom of the turn and slip indicator is another device, the inclinometer, which indicates whether the aircraft is skidding, slipping, or in coordinated flight. It operates independently from the gyro. Students will learn more about the function of the inclinometer in later slides.

Slide 22: The turn coordinator has largely replaced the turn and slip indicator in most modern airplanes, and is preferred by most pilots for its superior display qualities.

Unlike the turn and slip indicator, which uses a vertically mounted gyro, the turn coordinator's gyro is mounted at a slight angle (canted) to enable it to sense both roll and turn. Like the turn and slip indicator, the turn coordinator displays both the direction and rate of turn.

Rather than a needle, the turn coordinator uses a miniature airplane to show aircraft orientation. During a turn or roll to the right, the miniature airplane will dip toward the right; similarly, during a left-hand bank or turn, the miniature airplane will deflect downward to the left. Standard rate turns in both directions are indicated by markings on the face of the instrument. Pilots can establish a standard rate turn (3 degrees/second) by rolling the airplane until the miniature airplane on the display is aligned with one of those markings. Note that standard rate turns are also known as "2-minute turns," because at standard rate it takes two minutes for an aircraft to turn all the way around (360 degrees).

Like the turn and slip indicator, the turn coordinator includes an inclinometer, normally at the bottom of the display.

This brief video shows the inner workings of a turn coordinator, including how the display indicates turn direction and rate.

- "How a Turn Coordinator Works" (Length 2:50)
  http://video.link/w/lbVg

Slide 23: Though itself not gyroscopic, the inclinometer is normally attached to gyroscopic turn instruments. This device provides information concerning the quality of turns. It consists of a small ball suspended in a curved, horizontal tube of liquid. The ball is free to move left and right in the tube as the airplane turns and yaws. The liquid is there to dampen that movement.

The ball deflects within the tube in response to centrifugal force that exerts pressure on the ball during turns, moving it one way or the other. In a perfectly coordinated turn, the ball will remain centered in the tube, but in an uncoordinated turn—that is, a turn in which the pilot uses either too much or too little rudder—the ball will deflect away from its center point toward the left or right, in response to the yawing motion of the aircraft. To maintain coordinated flight, the pilot has to apply the proper amount of rudder to keep the tail in line with the nose of the airplane. This requires the pilot to apply rudder in the same direction as the ball is deflected. If the ball is deflected to the right, the pilot must apply more right rudder, and if the ball is deflected to the left, more left rudder is required.

Slide 24: The heading indicator is another gyroscopic instrument. Unlike the attitude indicator, which tells the pilot if the airplane is pitching or banking, the heading indicator displays directional information: that is, it shows the pilot the direction the nose of the airplane is pointed. The direction scale is measured in degrees, with the 0-degree point being magnetic north; all other headings are expressed in relation to this 0-degree point. For example, if the aircraft is headed in a direction 090-degrees clockwise from magnetic north, the heading indicator would show zero-nine-zero (ninety, which is East) degrees on its face. The heading of the aircraft is displayed at the top of the instrument, at the point where the airplane symbol meets the top of the rotating instrument face.

Although the heading indicator shows direction relative to magnetic north, it is not itself a magnetic instrument. It must be set prior to each flight to the heading indicated on the magnetic compass. The gyroscope inside the instrument maintains its rigidity in space, so when the airplane changes its heading the gyroscope remains in its original position and the card on the face of the instrument appears to rotate and settle at the new heading. What is in fact occurring is that the card is remaining stationary, and the aircraft is rotating around the card.

The heading indicator must be set to match the magnetic compass in order to provide an accurate reference to north. The advantage of the heading indicator over the magnetic compass is that the heading indicator does not exhibit the kinds of errors associated with the compass in flight. While the compass is prone to turning and acceleration errors, the heading indicator maintains its rigidity in space. As long as the heading indicator is set to the correct heading while the airplane is in straight and level, unaccelerated flight, the heading indicator will display an accurate heading and make flying precise headings much simpler for the pilot.

Slide 25: The gyroscope inside the heading indicator is mounted in the horizontal plane, with the rotor spinning vertically. The card at the face of the instrument is physically attached to the rotor, so it maintains its rigidity in space as the aircraft turns. In this respect, the heading indicator is much like the attitude indicator, except the heading indicator does not display bank and pitch information but rather heading.

The heading indicator is subject to unwanted effects as a result of gyroscopic precession and internal friction. As the gyroscope spins, it precesses in response to changes in the direction of the aircraft. This precession causes the heading indicator's readings to drift and become less accurate over time. Friction inside the instrument causes an imperfect rotation of the gyroscope, also creating inaccuracy. Pilots are trained to refer to the compass periodically in flight and to reset the heading indicator to match. A knob on the front of the heading indicator allows the pilot to reset the indicator when such drift and inaccuracy occurs.

Earth's rotation is another reason the heading indicator becomes inaccurate. The planet rotates at the rate of approximately 15 degrees per hour; if not corrected, the heading indicator would experience significant drift as a result of this rotation. When drifting occurs, the pilot simply adjusts the heading indicator to match the magnetic compass.

Slide 26: Another type of heading indicator is the horizontal situation indicator (HSI). The HSI combines a heading indicator with a VOR or other radio-based display.

Like the standard heading indicator, the HSI indicates the direction that the aircraft nose is pointed. Unlike the heading indicator, which requires periodic resetting to overcome drift and match the magnetic compass, the HSI gets its magnetic reference directly from another onboard source called a magnetometer. The magnetometer is not affected by magnetic dip, and therefore does not exhibit the kinds of errors associated with the magnetic compass. HSIs driven by magnetometers do not need to be reset nearly as often, as they are not subject to the same drift and inaccuracies experienced by heading indicators.

Many pilots prefer the HSI display over the standard heading indicator because it also provides navigation information they would otherwise obtain from another instrument. This combined instrument makes scanning far easier for the pilot and reduces workload and fatigue.

EXTEND

Teacher Materials: Gyroscopic Instruments Presentation, Gyroscopic Instruments Teacher Notes 3
Student Material: Gyroscopic Instruments Student Activity 3

Slide 27: Failure of the gyroscopic instruments, especially when operating in clouds, is usually an emergency situation. Pilots rely on their gyroscopic instruments to provide attitude information, and when that information is no longer available the pilot runs the risk of losing control of the aircraft.

Gyroscopic failure means that the gyros stop turning or have tumbled as a result of an unusual attitude of the aircraft. For vacuum or pressure-powered instruments, the most common cause of failure is pump failure. When vacuum or pressure pumps quit working, they no longer provide the power needed to drive the gyros and the instruments fail. Instruments can fail for other reasons, too. Normal wear and tear of the instrument itself, clogged air filters, or holes and leaks in the tubing that feeds pressure from the pump to the instrument can all cause failures. For electrically-powered gyros, electrical system failure of the aircraft or a failure of the electric motor that drives the gyro are the most common causes of the loss of function.

Another cause of instrument failure is a condition called *tumbling*. Tumbling occurs when either the pitch or bank of the aircraft exceeds the instrument's limits. Students were introduced to this idea in a video earlier in this lesson. The internal mechanism of the gyroscope loses its orientation as a result of being turned or twisted too far within the casing. This can occur during severe turbulence or when flying the airplane into unusual attitudes, such as when doing aerobatics. For most attitude indicators, the gyro will tumble when the bank exceeds approximately 100 degrees left or right or the pitch exceeds 60–85 degrees up or down. These attitudes are unlikely to occur during normal flight. In any case, the gyroscopic instruments will not be able to regain their functionality until they realign: that is, until they can regain their normal orientation within the instrument case and speed up to the required high RPM.

Slide 28: The failure of the vacuum system can be very subtle and difficult to recognize, at least at first. Normally, vacuum systems don't fail instantaneously; rather, the pressure being delivered to the instruments slowly decreases. This causes the instruments to slowly lose their accuracy rather than suddenly fail, often luring the unsuspecting pilot into unrecognized errors. Even during instances of sudden vacuum failure, the gyroscopes within the instruments themselves have a momentum that keeps them spinning for some time before they slowly unwind to total failure.

To increase the likelihood that the pilot will recognize an impending instrument failure, many systems are equipped with warning lights, alarms, or red flags that appear on the instruments when they are no longer operating properly or when vacuum or pressure is reduced.

Pilots are trained to catch imminent instrument failures by continuing to scan their instruments throughout all phases of flight. Good pilots will keep their eyes moving over the instrument panel at all times, including the pressure gauges and possible warning lights and alarms. In this way, developing failures can be caught early and dealt with. Pilots are also trained to use other instruments in the event of a gyroscope failure.

Slide 29: This brief video shows how an attitude indicator may behave when it loses its vacuum. The erratic behavior makes the instrument useless to pilots in flight. You may not need to show the full video. A few seconds should be enough for students to see what’s happening.

- “Malfunctioning Attitude Indicator” (Length 0:45)
  http://video.link/w/DnVg

This brief video shows how a heading indicator might respond in the event of a gyro failure. You may not need to show the full video. A few seconds should be enough for students to see what’s happening.

- “In-flight Vacuum Failure” (Length 0:44)
  http://video.link/w/5sXg

Slide 30: Flying without gyroscopic instruments in clouds, fog, or other conditions of reduced visibility is an emergency. Flying without reference to the horizon or other visual cues can cause spatial disorientation—a situation in which the body is tricked into misperceiving its orientation. For example, you may not be able to tell right side up from upside down, or you may have the sensation of turning to the left when you are actually turning to the right. Gyroscopic instruments can help prevent spatial disorientation by providing information the body cannot.

Pilots are trained to respond to instrument failure in a systematic way.

First, the failed instruments should be covered up so that they are taken out of the pilot's scan and cannot become distractions. Many pilots carry rubberized cover-ups for this very purpose, but if these aren't handy any strip of paper or tape will do. Next, the pilot focuses on the instruments that are still functioning properly. For example, if the attitude indicator and heading indicator have failed, the pilot will rely on the turn coordinator and magnetic compass for turn and bank information, and the altimeter and vertical speed indicator for pitch inputs. If the failure occurs when flying in clouds, the pilot would declare an emergency and advise Air Traffic Control of the failure, then request assistance in navigating to a nearby airport for landing. When flying with good visibility (e.g., outside of clouds), gyroscopic failure is less of a problem. In those cases, the pilot would simply fly to a nearby airport and land to have the equipment repaired.

Some aircraft are equipped with secondary systems to power the gyros in the event the primary system fails. For instance, many aircraft have two vacuum pumps in case one fails. Other aircraft may have an electric attitude indicator that can be referred to if the primary vacuum-driven attitude indicator fails. Having a secondary source of gyroscopic power is highly recommended for aircraft that fly under instrument conditions. The ability to turn to these secondary systems when needed increases flight safety.

Some onboard GPS systems, and many tablet-based aviation applications, have a built-in panel of attitude instruments that can be referred to in the event of instrument failure in the airplane. These instruments get their attitude information from a special attitude and heading reference system that uses the electronic equivalent of gyros to simulate rigidity in space and precession effects. The result is a set of low-cost, effective attitude instruments for emergency use.

Slide 31: Students will follow the instructions in **Gyroscopic Instruments Student Activity 3** to practice flying, under simulated conditions, during a failure of their plane's gyroscopic instruments. See **Gyroscopic Instruments Teacher Notes 3** for sample answers to the analysis questions.

EVALUATE

Teacher Materials: Gyroscopic Instruments Presentation, Gyroscopic Instruments Teacher Notes 4
Student Material: Gyroscopic Instruments Student Activity 4

Slides 32–39: Students will answer the Private Pilot Knowledge Exam Questions.

Slide 40: Conduct the **Summative Assessment**.

Summative Assessment

Distribute a copy of **Gyroscopic Instruments Student Activity 4** to each student. In this final assessment, students will demonstrate their depth of knowledge about gyroscopic instruments by answering a series of questions on topics including which instruments are gyroscopic, how are they powered, causes of failure, indications of failure, and correct responses to failure. Correct answers are provided in **Gyroscopic Instruments Teacher Notes 4**.

[DOK-L1: *Identify;* DOK-L2: *Describe]*

Summative Assessment Scoring Rubric

- Answers show evidence of the following:
  - Knowledge of the different types of gyroscopic instruments and how they are powered
  - Ability to read heading indicators
  - Understanding of the causes of gyroscope failure and how to respond

Points	Performance Levels
9	All questions are answered correctly, showing a complete and accurate understanding of gyroscope instruments, what they indicate, sources of failure, and correct responses to failure.
7-8	1-2 questions are answered incorrectly, showing minor gaps in understanding of gyroscope instruments, what they indicate, sources of failure, and correct responses to failure.
5-6	3-4 questions are answered incorrectly, showing major gaps in understanding of gyroscope instruments, what they indicate, sources of failure, and correct responses to failure.
0-4	5 or more questions are answered incorrectly, showing little understanding of this lesson's topics.

STANDARDS ALIGNMENT

NGSS STANDARDS

Three-dimensional Learning

- **HS-ETS1-3** - Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.
    - Science and Engineering Practices
        - Constructing Explanations and Designing Solutions
    - Disciplinary Core Ideas
        - PS2.A: Forces and Motion
        - ETS1.B: Developing Possible Solutions
    - Crosscutting Concepts
        - Structure and Function
        - Interdependence of Science, Engineering, and Technology
- **HS-ETS1-4** - Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.
    - Science and Engineering Practices
        - Using Mathematics and Computational Thinking
    - Disciplinary Core Ideas
        - ETS1.B: Developing Possible Solutions
    - Crosscutting Concepts
        - Systems and System Models

COMMON CORE STATE STANDARDS

- **RST.9-10.3** - Follow precisely a complex multistep procedure when carrying out experiments, taking measurements, or performing technical tasks, attending to special cases or exceptions defined in 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.
- **RST.9-10.5** - Analyze the structure of the relationships among concepts in a text, including relationships among key terms (e.g., force, friction, reaction force, energy).
- **WHST.9-10.9** - Draw evidence from informational texts to support analysis, reflection, and research.
- **MP.2** - Reason abstractly and quantitatively.
- **MP.6** - Attend to precision.

REFERENCES

Pilot's Handbook of Aeronautical Knowledge, pages 8-15 through 8-20
https://www.aopa.org/news-and-media/all-news/2017/november/flight-training-magazine/what-am-i-attitude-

indicator
https://www.aopa.org/training-and-safety/students/flighttestprep/skills/vacuum-system-failure\