Hypersonics STEM Curriculum

Forces of Flight

Grade	Time	Subject Area	Key Concepts
High School	45 min	Physics	Forces

Lesson Overview

In this lesson, students will draw a free body diagram (FBD) for several types of flight (subsonic, supersonic, hypersonic, spacecraft launch, and spacecraft return). The focus of the lesson is to practice using the length and direction of the arrows in the FBD to proportionally represent the magnitude and direction of the forces. This activity has students practice on both balanced (constant speed) and unbalanced (accelerated motion) forces. This lesson could be done as an introduction to FBDs or to reinforce the ideas.

This lesson could be done individually by students or within groups. Additionally, the instructor can let the students work at their own pace or regroup the class after each section of FBDs to debrief and check for understanding.

As a note, this lesson does not use abbreviations for the forces since different instructors may use different systems of labeling FBDs. For example, weight can be abbreviated as w, F_g, mg, etc. It is up to the instructor to decide how to (or not to) implement abbreviations.

NGSS & CCSS Standards

HS-PS2-1 Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.

Learning Objectives

By the end of this lesson, students will be able to:

- Explain the influence of the different forces impacting flight.
- Draw free body diagrams for several types of motion: horizontal, vertical, constant speeds, and changing speeds.
- Use free body diagrams to compare the magnitude and direction of different forces.
- Explain how the net force on an object relates to the motion of the object.

Essential/Overarching Question

How do the magnitude and direction of the forces on an aircraft differ for various types of flight?

Key Vocabulary

Speed – the rate at which an object is moving. Speed is calculated by dividing the distance travelled by the time it took to travel that distance.

Speed of Sound – the rate at which sound moves through a medium. The speed of sound depends on both the density and the temperature of the medium. The speed of sound through air at 20° C (68° F) at sea level is 343 m/s (767 mph).

Mach – the ratio of the speed of an object to the speed of sound, or how many times the speed of sound an object is moving. It is often followed by a number indicating the ratio; for example: Mach 1 is the speed of sound, Mach 2 is twice the speed of sound, Mach 5 is five times the speed of sound.

Sonic – speeds equal to the speed of sound (Mach 1).

Subsonic – speeds smaller than the speed of sound (less than Mach 1).

Transonic – speeds near (Mach 0.8-1.2) the speed of sound where drag is highest (e.g. sound barrier).

Supersonic – speeds greater than the speed of sound (Mach 1 and greater).

Hypersonic – speeds greater than five times the speed of sound (Mach 5 and greater).

Fluid – a substance with no fixed shape; a liquid, gas, or plasma. A substance that flows when an external force is applied to it.

Flow – the motion of a fluid (liquid, gas, or plasma) when it experiences unbalanced forces.

Force – a push or a pull on an object or system.

Net Force – the vector sum of all forces acting on an object or system.

Mass – the amount of matter in a body; measure of inertia or resistance to change velocity.

Acceleration – the rate an object changes velocity; a change in velocity over time.

Weight – the gravitational force acting on an object; $w = m*g$.

Lift – is the vertical component of the force on an aircraft's wing or airfoil resulting from a pressure imbalance in the flow stream moving around the wing/airfoil. The direction of lift is typically perpendicular to the flow stream.

Drag – the force that opposes the motion of an object traveling through a fluid; aerodynamic friction. It is caused by the interaction between a solid and a fluid.

Thrust – the propulsion force that moves a solid through a fluid.

Free Body Diagram (FBD) – a representation of all the forces acting on an object or system. The object or system is represented by a dot or box. The forces are represented by arrows coming out of the dot or box where the arrow points in the direction of the force and the length of the arrow is proportional to the magnitude of the force.

Science Concepts Overview

There are four forces that affect objects in flight: lift, weight, thrust, and drag. Lift is the force on a wing caused by the flow (moving fluid – air in our case) around the wing. The force is perpendicular to the direction of the flow (up or down on a typical aircraft). Weight is the downward gravitational pull on an object. Thrust is the propulsion force that moves the object through a fluid, usually created by an engine. And drag is the frictional force that opposes the motion of an object moving through a fluid.

When looking at how those four forces combine to move an object, we look at the net force. Net force is the vector sum (treat x- and y-axis separately) of all objects acting on an object or system of objects. The net force points in the same direction as the acceleration, but not necessarily in the same direction as the motion of the object. If the net force and the motion of the object are in the same direction, the object increases in speed. If the net force and the motion of the object are in the opposite direction, the object decreases in speed. And if the net force is zero, the object is either moving at a constant speed or is not moving.

Materials List

- ☐ Scissors
- ☐ Forces of Flight handout (one per student)
- ☐ Model Free Body Diagram (one per student or group)
- ☐ Forces of Flight Exit Ticket (one per student – there are two exit tickets per page)

Lesson Preparation

Prior to the lesson, the instructor should gather materials and make copies of the Forces of Flight handout, Model Free Body Diagram, and Forces of Flight Exit Ticket.

Safety

There are no additional safety concerns beyond normal classroom procedures for this lesson.

Procedure

Engage (15 minutes)

1. Pose the following question to the class:
    - In our “real lives,” we use many physics terms, but they may not have the same meaning as how we use them in physics class. Today, we are going to

learn about the four forces that affect flight: thrust, weight, drag, and lift. I am guessing that you have used or heard of those words before. Using your prior experiences, how would you define: thrust, weight, drag, and lift? Write your definitions on the Forces of Flight handout.

2. Give students a couple minutes to use their prior knowledge to define thrust, weight, drag, and lift on their Forces of Flight handout.
3. Have students share their definitions of thrust, weight, drag, and lift. As students share, record their ideas in a place where the entire class can see.
4. As a class, use the students' prior knowledge to build a class definition that aligns with the scientifically accepted definition for each of the four forces. Have students update their definitions on the Forces of Flight handout.

Explore/Explain/Elaborate (25 minutes)

5. Students can work individually or in groups.
6. Prior to working on the Forces of Flight handout, students should cut out the pieces for their model FBD.
7. Students will work through three groupings of FBDs. In each grouping, the students will go through the explore, explain, elaborate cycle.
8. For each grouping of FBDs students will start by using the model FBD to *explore* how the forces interact during each specific flight example.
9. Students will then *explain* their final understanding by drawing and labeling a FBD. Students are also asked to label the net force and the direction of the motion outside of their FBD.
10. Students will be asked to further *elaborate* on their understanding of the forces of flight by answering questions after each grouping of FBD.

Evaluate (5 minutes)

11. At the end of the lesson, students complete the Forces of Flight Exit Ticket. The exit ticket asks three questions, one that checks their understanding of the lesson and two that extend their thinking:
    - Draw and label the FBD of an airplane speeding up to the left. Include separate arrows next to the FBD showing the direction of the motion and the net force.
    - Airplanes tend to take off at an angle while speeding up. Draw and label a FBD for an airplane taking off. Include separate arrows next to the FBD showing the direction of the motion and the net force.
    - As an aircraft flies, it burns fuel to provide the thrust. Describe how that would affect the FBD.

STEM Career Connections

- Aerospace engineering
- Military aircraft design
- Pilot – commercial and military

Extensions

The *engage* discussion could be done as a think pair share where each pair (or group) is asked to combine their definitions to make a common definition. Then the pairs (or groups) share their definitions to the class where again you work to create a common, scientifically correct, definition.

The FBDs from the *explain* section could be used to practice building equations using Newton's 2^{nd} Law.

The *explain* and *elaborate* sections could be expanded to have students work on more complicated FBDs where the forces are not perpendicular to one another such as aircrafts flying at angles.

The *elaborate* section could be expanded by having students build paper airplanes and explain how they use the design of their airplanes to change the effect of the different forces. (ex. wing shape - lift, adding paper clips - weight, throwing the paper airplane - thrust, airplane design - drag)

Students could further their study of lift by completing the Hypersonics High School Physics Lesson Plan – Can I Give You a Lift? In this lesson, students design model aircraft wings and evaluate the magnitude of lift the wings create in a wind tunnel.

References & Resources

Elert, G. (2022). *Aerodynamic drag*. The Physics Hypertextbook. https://physics.info/drag/#:~:text=1%20Drag%20increases%20with%20the%20density%20of%20the,induced%20drag%20%29%2C%20boundary%20layer%20separation%2C%20and%20

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National Air and Space Museum. (n.d.) *The four forces*. How Things Fly. https://howthingsfly.si.edu/forces-flight/four-forces

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Name: ____ Date: __________________

Forces of Flight

✈ There are four forces that are involved in flight. Thrust, weight, drag, and lift. In your own words, define those four forces:

Thrust – ____

____

Weight – ____

____

Drag – ____

____

Lift – ____

____

✈ In the sections that follow, you are being asked to compare the FBDs of three different aircraft motions. For each scenario, use your model free body diagram (FBD) to decide how the forces align. Move the force arrows to point in the direction that they are acting and adjust the length of the force arrow to show a difference in magnitude (size).

Once you have decided the final placement of the arrows on your model FBD, record and label the FBD in the table. In addition, outside of your FBD, draw and label an arrow indicating the direction of the net force and the direction of the speed (motion).

Subsonic Motions

FBD for an airplane moving right at constant speed.	**FBD for an airplane speeding up to the right.**	**FBD for an airplane slowing down to the right.**

How did the FBDs (including motion and net force) change for those three different motions?

How would the FBDs change if the airplanes were moving to the left?

Subsonic vs. Supersonic vs. Hypersonic

✈ Drag is affected by many factors. Drag increases with density of the fluid, area, and *speed*. Drag can also be influenced by other features such as texture, shape, and viscosity.

FBD for a subsonic aircraft moving right at a constant speed.	FBD for a supersonic aircraft moving right at a constant speed.	FBD for a hypersonic aircraft moving right at a constant speed.

How are these FBDs different?

How would these FBDs change if the aircrafts were speeding up?

How would these FBDs change if the aircrafts were slowing down?

Airplane vs. Spacecraft

✈ While aircrafts tend to take off and land at relatively small angles (5°-15°) with the horizon, spacecrafts launch and return to space at angles that are closer to vertical (70°-80°). For our purposes, we can assume the spacecraft launches and returns completely vertically

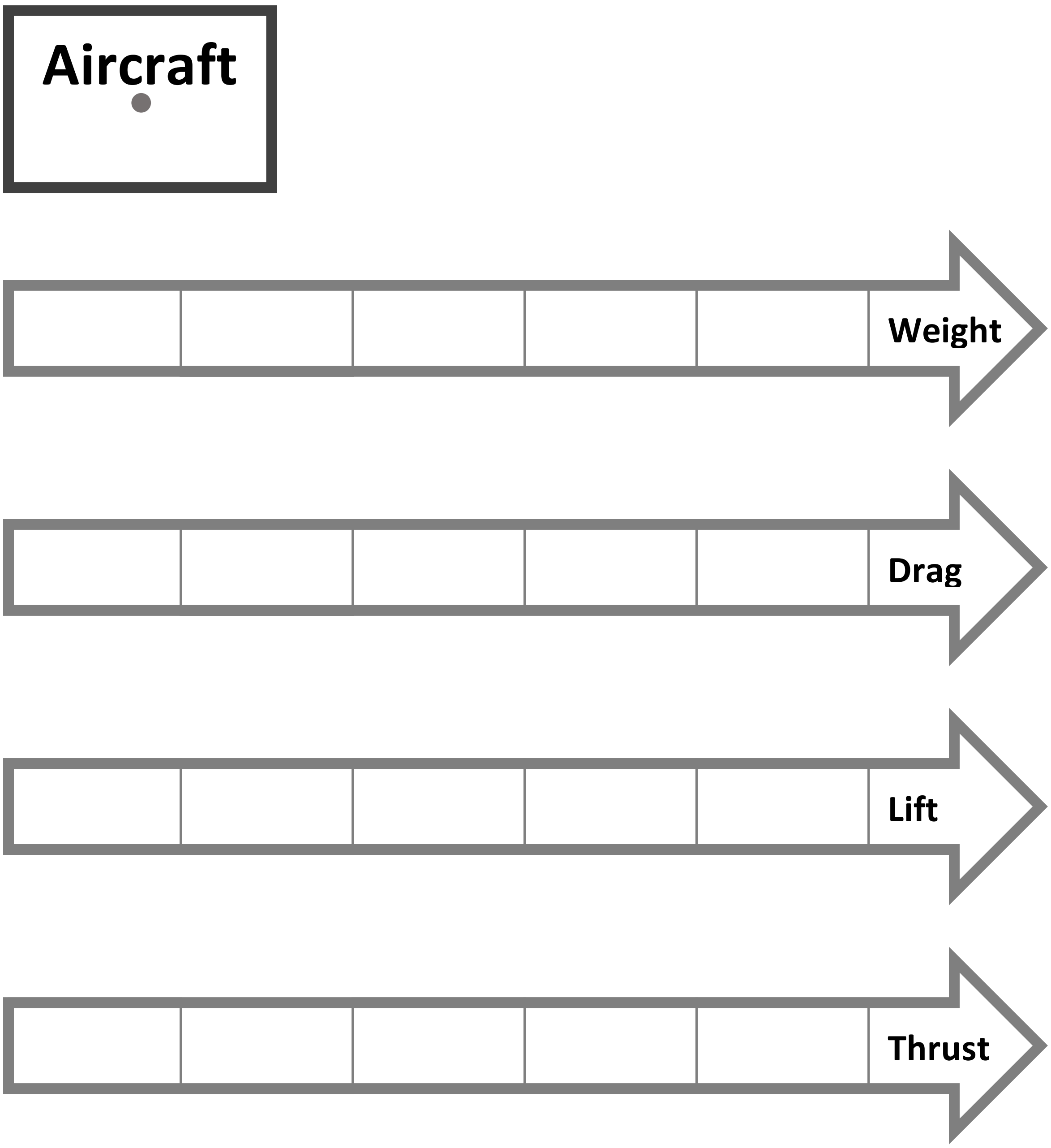
FBD for an airplane speeding up to the right.	FBD for a spacecraft launching (accelerating up).	FBD for a spacecraft returning (accelerating down).

How did the FBDs change for those three different motions?

If the spacecraft launching turned off the thrusters, how would that change the FBD, the net force, and the direction of the motion?

Model Free Body Diagram

✂ Cut out the aircraft box and the four force arrows.



Name: ____ Date: ___________________

Forces of Flight Exit Ticket

1. Draw and label the FBD of an airplane speeding up to the left. Include separate arrows next to the FBD showing the direction of the motion and the net force.

2. Airplanes tend to take off at an angle while speeding up. Draw and label a FBD for an airplane taking off to the right at a 15° angle. Include separate arrows next to the FBD showing the direction of the motion and the net force.

3. As an aircraft flies, it burns fuel to provide the thrust. As the fuel burns off, that mass is no longer part of the system. Describe how that would affect the FBD.

Name: ____ Date: ___________________

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1. Draw and label the FBD of an airplane speeding up to the left. Include separate arrows next to the FBD showing the direction of the motion and the net force.

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3. As an aircraft flies, it burns fuel to provide the thrust. As the fuel burns off, that mass is no longer part of the system. Describe how that would affect the FBD.

Name: _Answer Key____ Date: ______________________

Forces of Flight

✈ There are four forces that are involved in flight. Thrust, weight, drag, and lift. In your own words, define those four forces:

Thrust – the propulsion force that moves a solid through a fluid

Weight – the gravitational force acting on an object; w = m*g

Drag – the force that opposes the motion of an object traveling through a fluid; aerodynamic friction. It is caused by the interaction between a solid and a fluid

Lift – the force on an aircraft's wing or airfoil. The direction of the force is perpendicular to the oncoming flow direction.

✈ In the sections that follow, you are being asked to compare the FBDs of three different aircraft motions. For each scenario, use your model free body diagram (FBD) to decide how the forces align. Move the force arrows to point in the direction that they are acting and adjust the length of the force arrow to show a difference in magnitude (size).

Once you have decided the final placement of the arrows on your model FBD, record and label the FBD in the table. In addition, outside of your FBD, draw and label an arrow indicating the direction of the net force and the direction of the speed (motion).

Subsonic Motions

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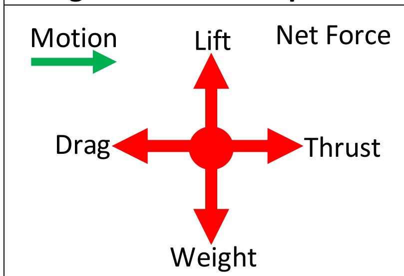	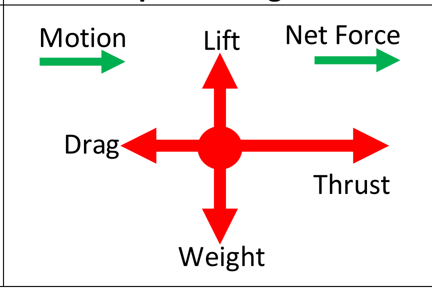	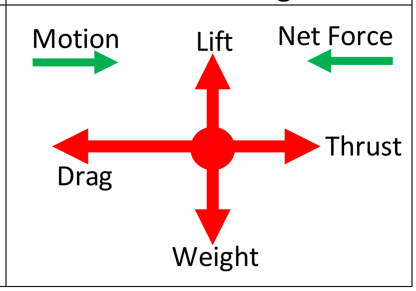

How did the FBDs change (including motion and net force) for those three different motions?
The length of the thrust force changes. It is the same length as the drag when at constant speed, longer than drag when speeding up, and shorter than drag when slowing down. Net force and motion are in the same direction when speeding up, opposite when slowing down.
How would the FBDs change if the airplanes were moving to the left?
The thrust and the drag would switch directions.

Subsonic vs. Supersonic vs. Hypersonic

✈ Drag is affected by many factors. Drag increases with density of the fluid, area, and *speed*. Drag can also be influenced by other features such as texture, shape, and viscosity.

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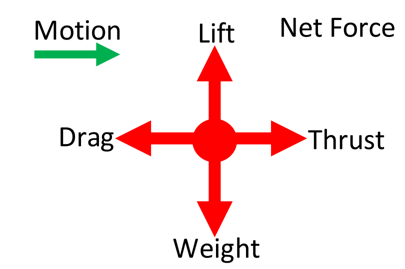	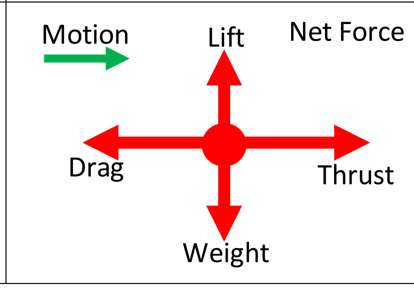	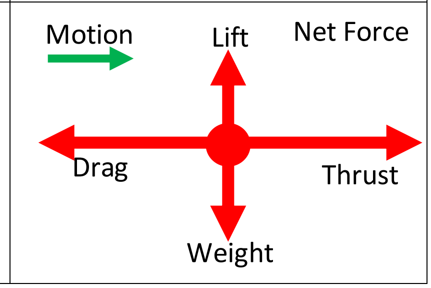

How are these FBDs different?

Both the thrust and the drag arrows get longer as the aircraft speed increases.

How would these FBDs change if the aircrafts were speeding up?

If they were speeding up, the thrust arrow would be longer than the drag arrow.

How would these FBDs change if the aircrafts were slowing down?

If they were slowing down, the thrust arrow would be shorter than the drag arrow.

Airplane vs. Spacecraft

✈ While aircrafts tend to take off and land at relatively small angles (5°-15°) with the horizon, spacecrafts launch and return to space at angles that are closer to vertical (70°-80°). For our purposes, we can assume the spacecraft launches and returns completely vertically

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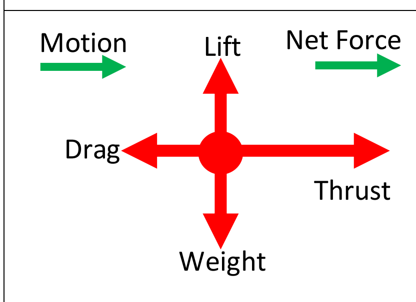
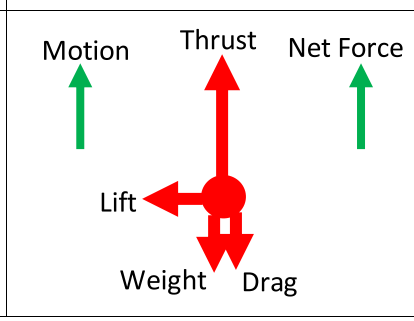
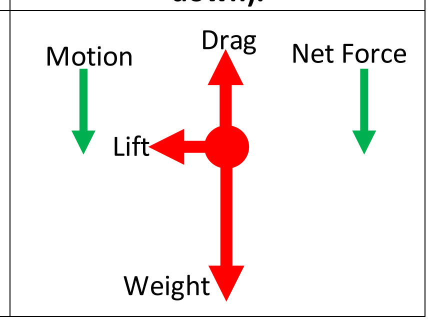
		

How did the FBDs change for those three different motions?

The thrust and drag are now vertical. There is no need for thrust when returning (free fall)

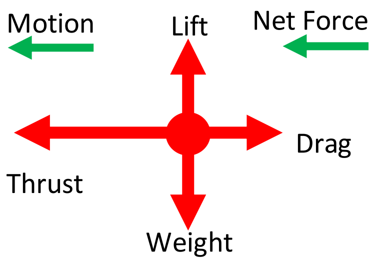
If the spacecraft launching turned off the thrusters, how would that change the FBD, the net force, and the direction of the motion?

There would no longer be a thrust force. The net force would be down and motion still up.

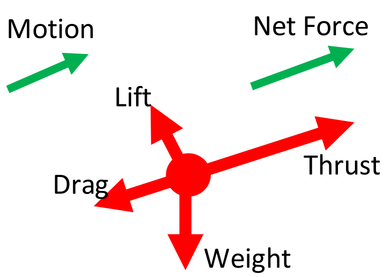
Name: _Answer Key_______________________________________ Date: ____________________

Forces of Flight Exit Ticket

1. Draw and label the FBD of an airplane speeding up to the left. Include separate arrows next to the FBD showing the direction of the motion and the net force.



2. Airplanes tend to take off at an angle while speeding up. Draw and label a FBD for an airplane taking off to the right. Include separate arrows next to the FBD showing the direction of the motion and the net force.



3. As an aircraft flies, it burns fuel to provide the thrust. As the fuel burns off, that mass is no longer part of the system. Describe how that would affect the FBD.

As the airplane burns fuel, the mass would decrease, decreasing the weight of the airplane. This would cause an unbalanced force upward unless the pilot accounted for it.