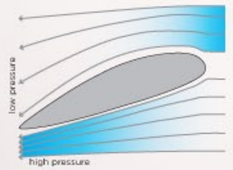
FOUR FORCES OF FLIGHT

HOW WOULD YOU DESIGN AN AIRCRAFT? IMAGINE YOU ARE A FLYING MACHINE. WHAT DO THE FOUR **FORCES** OF FLIGHT FEEL LIKE ACTING ON YOUR BODY? HOW WOULD YOU GENERATE MORE LIFT? MAKE YOURSELF FASTER OR MORE ENERGY EFFICIENT?

Force: A measurable push or pull in a certain direction.

LIFT

Lift: The force that makes an airplane wing or helicopter rotor rise and helps the aircraft escape the pull of the earth (gravity). Lift is a result of differences in air pressure, as is explained by Bernoulli's Principle, and equal and opposite forces, as explained by Newton's laws.



Bernoulli's Principle: Developed by Swiss mathematician Daniel Bernoulli, this principle states that the pressure of a flowing fluid or gas decreases as the velocity increases and increases as the velocity decreases.

Airfoil: A fin that provides lift when a current of air passes over it. Bird wings and most airplane wings are airfoils. An airfoil operates according to *Bernoulli's Principle.*

Air pressure: The force exerted by air molecules, measured over a given area of surface.

Glider. Without an engine, airplanes are unable to produce their own thrust. Planes without engines are called gliders, sailplanes, or hang gliders. These engine-less planes are able to glide if there are special upward winds called thermals or if the plane gets a tow to a higher altitude by an engine-powered airplane.

Early aircraft had airfoils that were inspired by the wings of birds and fins of sharks. The profile of the albatross' wing shows the familiar shape of an airfoil. The bird can use its muscles to adjust the angle of its wings, either increasing or decreasing the amount of lift that it wants.

A plane's engine moves it forward, causing a collision between the wing and the air. This collision, combined with the shape of the airfoil, creates downwash. The equal and opposite force from the downwash creates upward lift on the wing.

DRAG

Drag: The force that opposes thrust. Drag is a result of the displacement of air when an object moves through air. Drag must be overcome in order for an airplane (or anything else) to move forward through a gas or liquid. Other terms for drag are *wind resistance* and *friction.*

Drag slows an aircraft down, making flights longer and more expensive. Large engines are required to overcome the force of drag and propel the aircraft forward. These heavy engines need strong structural supports throughout the aircraft and require costly fuel.

Control through drag.
By increasing the drag on specific parts of the plane, small flaps called ailerons, elevators, and rudders make it possible for the pilot to control the flight of the airplane.

Pitch. The elevators are on the tail of the aircraft. They make the nose of the airplane pitch up or down. If you raise the elevator, the tail drops down and the plane pitches up. If you lower the elevator, the tail comes up and the plane pitches down.

Roll. There is an aileron on the back edge of each wing. Ailerons make the plane roll side to side, which dips each wing up or down. By moving the ailerons in opposite directions, you can make the plane roll.

Yaw. The rudder makes the airplane yaw, which turns the nose of the airplane toward the right or left. If you move the rudder to the right, the plane yaws the right. If you move the rudder to the left, the plane yaws to the left. To make the plane turn, you must roll and yaw at the same time.

GRAVITY

Gravity: The force exerted by massive objects on other massive objects over a distance. The closer the objects are to each other, the stronger the force of attraction becomes.

In the famous story, **Sir Isaac Newton** (1643-1727) watched an apple fall from a tree and was inspired to investigate the force that pulls objects to the ground and holds the Moon in its orbit.

Newton's Laws of Motion

1. Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it.
2. The relationship between an object's mass (m), its acceleration (a), and the applied force (F) is F=ma. Acceleration and force are vectors. In this law, the direction of the force vector is the same as the direction of the acceleration vector.
3. For every action there is an equal and opposite reaction.

In a scene from *Legends of Flight,* Chief Test Pilot Mike Carriker draws an aircraft in space with the aid of a 3D drafting tool. Aircraft design is about shaping a flying machine that most appropriately balances the four interrelated forces of flight: minimizing weight to reduce the influence of gravity; maximizing lift; reducing drag and; maximizing thrust.

Newton: A unit used to measure force. One Newton equals 102 grams (3.60 oz), the approximate weight of one apple.

THRUST

Thrust is the force that pushes an airplane forward and allows enough air to run above and below the wing in order to create lift. Developing thrust was the final hurdle for the early pioneers of flight in getting aircraft off the ground. Thrust is the force that opposes drag and can be achieved by either pulling or pushing the airplane in a forward direction.

Jet Turbine. Jet turbine engines push air through the blades of a spinning turbine, which compresses the air. Fuel is then combined with the air and ignited. When the fuel burns, it rapidly expands from liquid to a gas and is forced out the rear of the engine. As the gas is forced out, the airplane is pushed forward.

Harrier Jump Jet. These amazing aircraft are called V/STOL (Vertical/Short Take-Off and Landing) airplanes. They use jet turbine engines for forward thrust, just like a standard jet. But what makes these planes special is their ability to change the direction of their jet nozzles. When they land and take off, their jets can be pointed straight down, allowing the jump jet to lift straight off the ground. Harriers can even hover like hummingbirds.

The Film. *Legends of Flight* is an inspiring and exciting documentary for IMAX® and other Giant Screen theaters featuring milestone 20th century aircraft, including the Stearman wooden biplane, Constellation, Harrier Jump Jet and Schleicher glider. Discover the design challenges, financial risks and the many lessons learned from a century of aviation trial and error, bringing us to the dawn of a new era of revolutionary aircraft—Boeing's 787 Dreamliner and the Airbus A380. Witness the construction and final assembly of the 787, and join 787 Chief Pilot Mike Carriker as he puts the new airliner through its rigorous test flights.

Credits
Educational materials for this film have been made possible by the generosity of The Boeing Company.

This *Legends of Flight* **Classroom Poster** is based on the Legends of Flight **Teacher's Guide**, available at: http://legendsofflightfilm.com/?loadedEducation=1

DIRECTED BY STEPHEN LOW PRODUCED BY PIETRO L. SERAPIGLIA A PRODUCTION OF JETLINER FILMS INC. IN ASSOCIATION WITH K2 COMMUNICATIONS
NARRATED BY JAMES LAHTI DIRECTOR OF PHOTOGRAPHY MARK PURHER EXECUTIVE PRODUCERS BOB KRESSER, JAN BAIRD
IN ASSOCIATION WITH THE SMITHSONIAN NATIONAL AIR AND SPACE MUSEUM

Building a modern jetliner involves thousands of people with different specialities working in countries around the world. In the case of the new Boeing 787 Dreamliner, the scope of international collaboration has been unprecedented.

BUILDING AN AIRPLANE

HOW DO YOU **BUILD A FLYING MACHINE?** HOW LIGHT WOULD IT NEED TO BE? HOW STRONG? WHAT MATERIALS WOULD YOU USE? WHO WOULD HELP YOU BUILD IT?

SWEDEN
GERMANY
FRANCE
UNITED KINGDOM
ITALY

Landing Gear
Engines
Fuselage
Doors
Brakes
Seats
Tubing
Ducts
Wiring

Boeing had to design and build an airplane that could carry the major structural components of another airplane. The result is the Dreamlifter, a modified Boeing 747 that has a hump-shaped back, no passenger windows, and a tail that swings on a huge hinge to open the plane for cargo loading.

Building the 787. Partners in eleven different countries across four continents were selected to build parts and design systems that would all fit together into one airplane. The major structural components of the 787 Dreamliner are built in Japan, Italy, Kansas, and South Carolina.

JAPAN
SOUTH KOREA
AUSTRALIA

Fuselage
Tires
Sound System
Lavatories
Wing Tips

The Boeing Company's Everett Plant in the state of Washington is the final assembly facility for the 787 and the largest building (by volume) in the world.

EVERETT, WA
Final Assembly, 787

UNITED STATES
CANADA

Escape Slides
Electronics
Software
Displays
Hydraulics

In 2011, an additional final assembly plant will be activated in South Carolina.

Lighting
Electronics
Water Systems
Seats
Sidewalls

Flight Deck
Fuel Gauge
Lighting
Engines
Windows
Fuselage

The 787 Dreamliner employs carbon fiber based composites (CFRP—carbon fiber reinforced polymer) in many major structural components including fuselage and wings. The goal of using composite materials is to reduce weight while preserving or increasing strength and reducing materials fatigue. Reducing weight contributes to fuel efficiency and aircraft range.

Composites also have better wear, fatigue and corrosion characteristics than aluminum, increasing reliability and reducing maintenance costs.

Composite: A new material made by combining two or more ingredient materials, each with its own distinct physical or chemical properties. When combined, the features of each ingredient are shared and the composite benefits beyond the individual parts. In a composite, there must be a reinforcement ingredient, which provides the structure, and a matrix ingredient, which is the binding agent.

For more information on this giant screen experience, visit:
www.legendsofflightfilm.com

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An early star of commercial aviation, the four-engine, turbo-prop *Super Constellation* which first flew in 1943, was constructed principally of aluminum.

LEGENDS OF FLIGHT

Early aircraft like the Stearman biplane used as a trainer during World War II (above) or the Wright Flyer (1903) pictured below, featured wooden frames with stretched and treated fabric (canvas) to form the outer windproof shell.

ALUMINUM

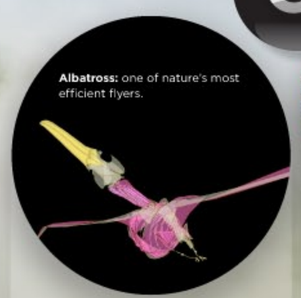
Aluminum. Aluminum is the most abundant *metal* on Earth.

Aluminum: extruded, cast and milled or rolled, this metal has been the key material for most commercial aircraft built over the last century. Aluminum is light and reasonably strong and can be shaped with high precision.

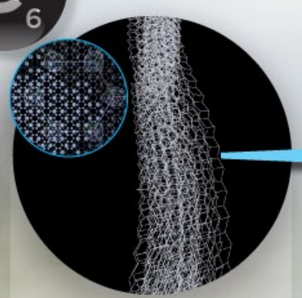
Composites. The giant double-decker Airbus A380 marked an important transition from all-aluminum construction to the use of a mix of aluminum and newer composite materials for some major aircraft components.

CARBON

Carbon. Carbon is the 4th most abundant element in the universe by mass and the 2nd most abundant in the human body after oxygen. The element is present in all known life-forms and is a constituent of DNA. Graphite and diamond are two of the best known forms of pure carbon.



Carbon. The element *carbon* is a basic building block of nature and a vital constituent of all life, including nature's flyers. Carbon also plays a vital part in some new building materials known as composites.



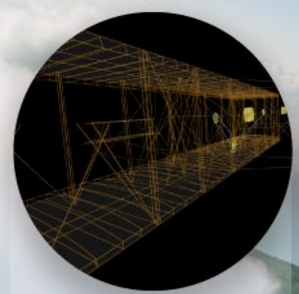
To form the composite **carbon fiber**, carbon atoms are formed into crystalline chains. These extremely fine filaments are then twisted into fibers called *threads* which in turn are woven together and mixed with epoxy resin to form a material called a *tape*.

CARBON FIBER

Through an intricate process of weaving, layering, mixing with resin, pressing and cooking with heat and pressure (in an autoclave)—carbon fiber tape is formed into specific composite components for the aircraft.

A Lighter Plane. Components shaped from carbon fiber composites have the property of being at least as strong as comparable metal parts, but less dense. This means aircraft can be built lighter and perform more efficiently in the air.

WOOD



Wood is a carbon-based material, composed substantially of naturally interwoven strands of cellulose fiber. Some small aircraft are still built with wood components today.

Like the original tree bending in the wind, **wood** retains high tensile strength, which is useful in aircraft construction. However, it's tendency to change moisture content and its inferior strength in compression have limited its use in aircraft.