UNDERSTANDING AIRPLANES


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This is so that the correct pairs of slides can be seen at the same time:
Slides 8 and 9, slides 10 and 11, slides 12 and 13, etc.
See slide 359 for more details.

Proprietary Information reminder: We are not at Boeing!

This course is popular among Boeing employees. However, it is open to the public. Many people in the room during these lectures are NOT Boeing employees!
Do not discuss Boeing proprietary information, i.e. details about Boeing products (or processes) that have not been released by Boeing to the public in books, articles / conferences, exhibits, press releases / interviews, documentaries / TV shows, or Boeing's website / YouTube channel, etc.

The way I think about it: I'm just going to pretend that all of the students taking this course are Airbus employees!

Along similar lines: The observations, conclusions, generalizations, and opinions expressed here are my own, not my employer's.
I am not a Boeing spokesperson, I do not represent Boeing.

General Disclaimer: I don't know everything

I have an academic background in aerodynamics (wind tunnel research into lift and drag), have done plenty of propulsion projects and classes (e.g. designing, fabricating, and testing components for aerospace engines, and writing code to model the thermodynamic behavior of said engines, i.e. their temperatures and pressures and thrust and fuel efficiency), currently work as a structures engineer and researcher, am a pilot, and have helped to design and built and test a UAV control system. So I think I do have a better overall understanding of how airplanes work than do most people at Boeing, who rarely look outside their niche.

However, I don't know ***all*** the specific details about how ***all*** airplane features work, why they are shaped the way they are, or the history of how they got that way. There are questions you may have that I don't know the answers to, and if you ask them, I will let you know. "Why exactly do the turbofan nozzles on the 787 and 747-8 have scalloped 'chevron' edges?"; I'm not really sure. All I know is that they help the turbofan air mix with the free-stream air in a way that makes less noise and is more fuel-efficient (and I think they save weight too). Beyond that, you'll have to ask an expert in that particular field. But, again, for most airplane parts, I honestly think that I can give a better answer than most people (including most academics and most Boeing people) about why it has its shape, how it works, and the history of how it got this way.

Technical note – Embedded videos: Slides 16, 48, 57, 60, 62, 69, 133, 180, 188, 226, 236, 250, 252, 254, 256, 280, 288, and 308 of this PDF contain videos. Videos might not play properly if this PDF is viewed in non-Adobe software.

Bernardo Malfitano

Academic

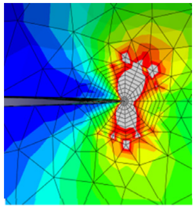
- B.S. Mechanical Engr., Stanford University
- M.S. Mechanical Engr., Columbia University
  Elective courses, lab work, and research topics included airplane design, aerodynamics, control systems, and propulsion

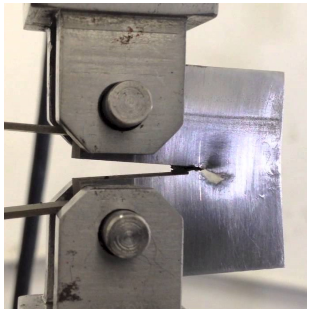
Hobbies

- Articles and photos on various aviation magazines, websites, & books, since 2003
- Pilot, RV-6 owner. 1st solo: 2009
  1st aerobatic solo: 2012
  1st flight to Oshkosh: 2014

Professional

- Boeing Commercial Aviation Services
  (Fleet support, structural analysis of repairs, maintenance planning); Long Beach: 2007-2008
- BCA Structural Damage Technology
  (Fatigue & Fracture Mechanics allowables testing and analysis methods development); Everett: 2009-2018
- BCA Airplane Configuration & Integration
  (Product Development); Harbour Pointe: 2018-Present





"Understanding Airplanes" Agenda

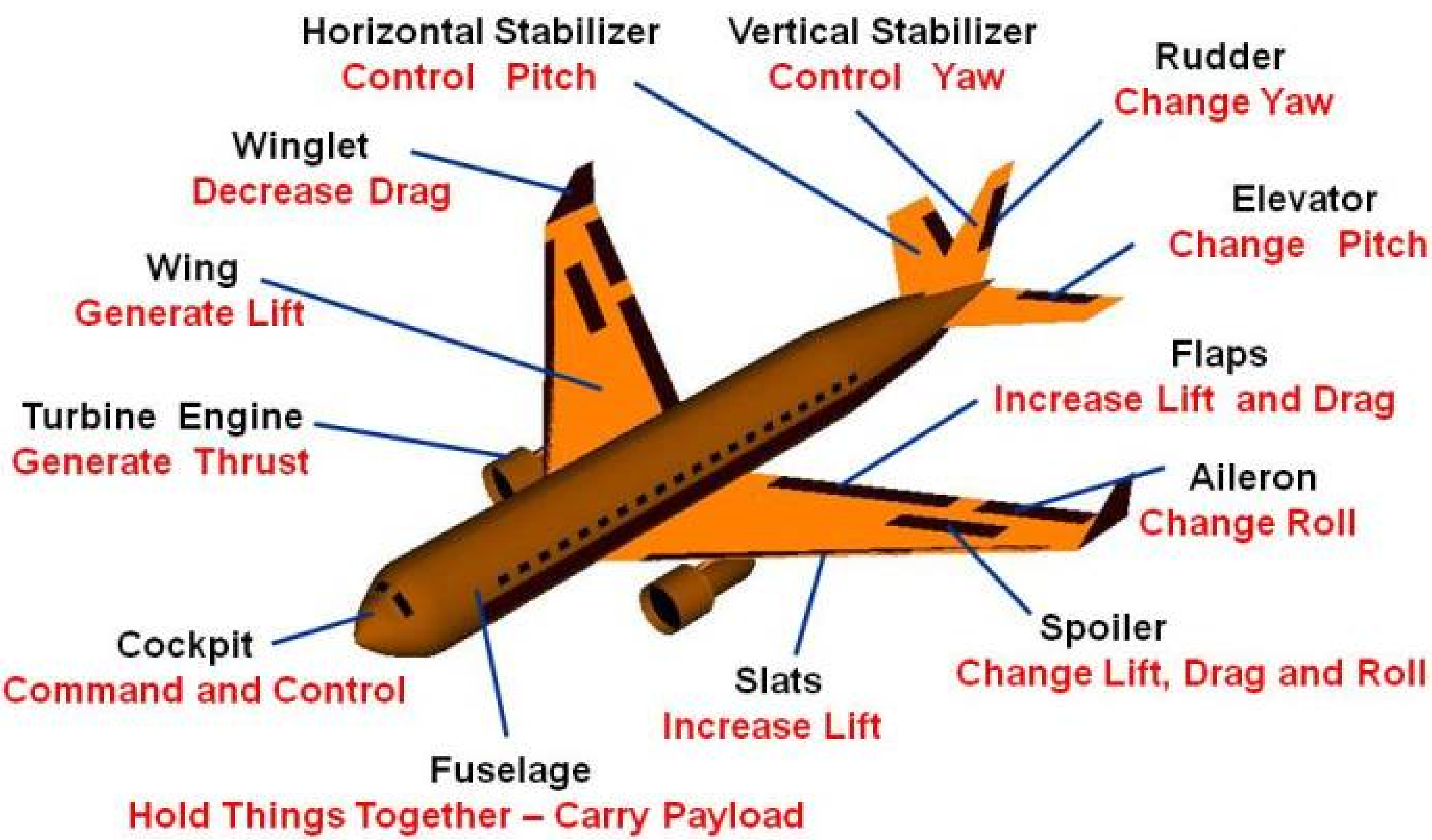
- Everything I say will be written on the odd-numbered slides.
- So: Don't worry about taking notes.

- I will say all the things written on the odd-numbered slides.
- So: You're better off just listening to me talk, rather than trying to read the paper while I'm talking ☺

Note: In the interest of time, this course blasts through most of the content without diving in depth. Many interesting topics and fascinating aeronautical projects are only quickly mentioned, or discussed for a minute or two, but each of them would make for a terrific book or course all by itself. These slides contain enough names and terms so that you can research further if any aircraft or topic sounds interesting to you. Just go to Google, Wikipedia, etc.

Note: These ~340 slides are for the ten-hour version of the "Understanding Airplanes" course, which focuses only on commercial airliner technology. Visit www.UnderstandingAirplanes.com for additional slides, which also covers topics such as stealth airplane design, aerobatics, uses of 3D printing in aeronautics, etc.

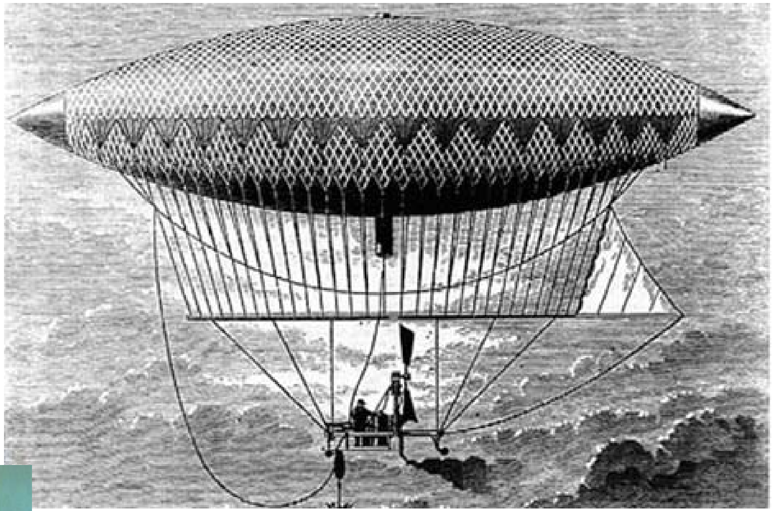
The Modern Airplane



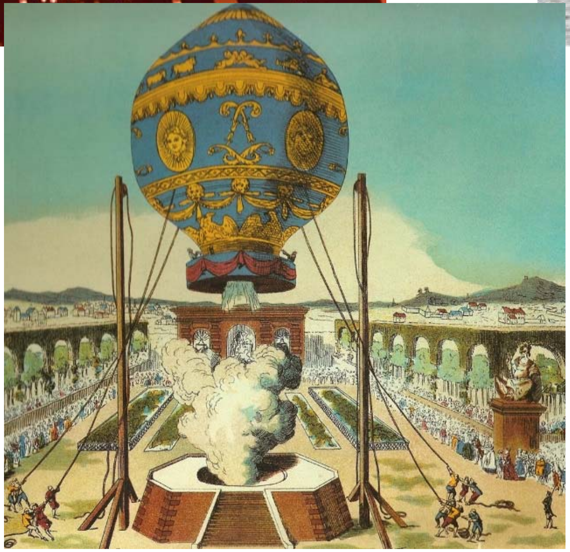
Aviation History

Lighter than air

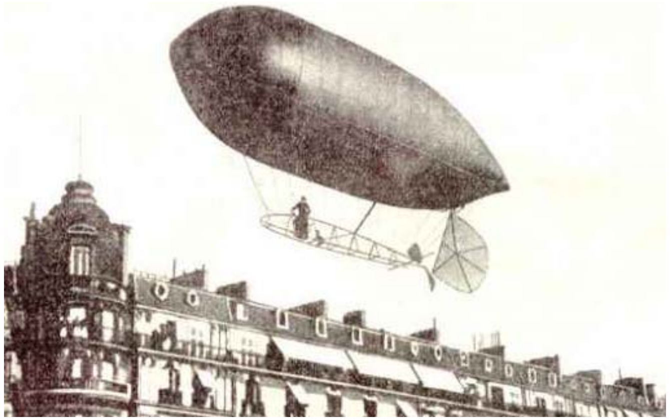
GIFFARD



KONGMING LANTERN



MONTGOLFIER



SANTOS DUMONT

Lighter than air

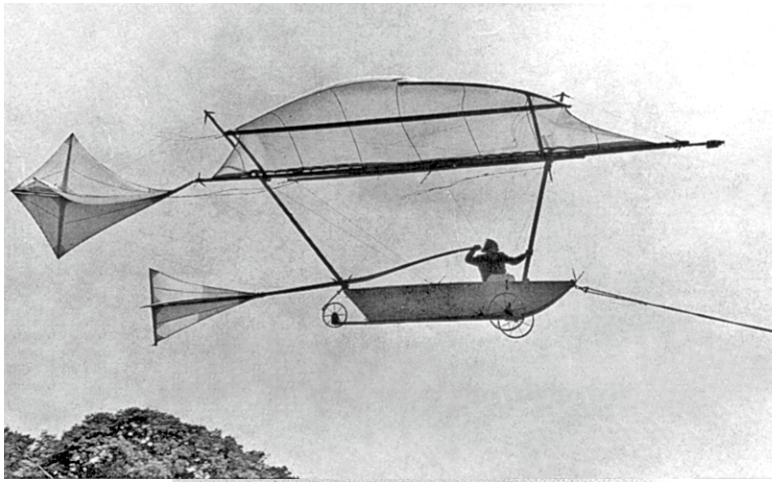
Same challenges as airplanes:

- Lightweight but strong and stiff structure
- For dirigibles: Lightweight engines, propellers
- For dirigibles: low drag, balance, controllability

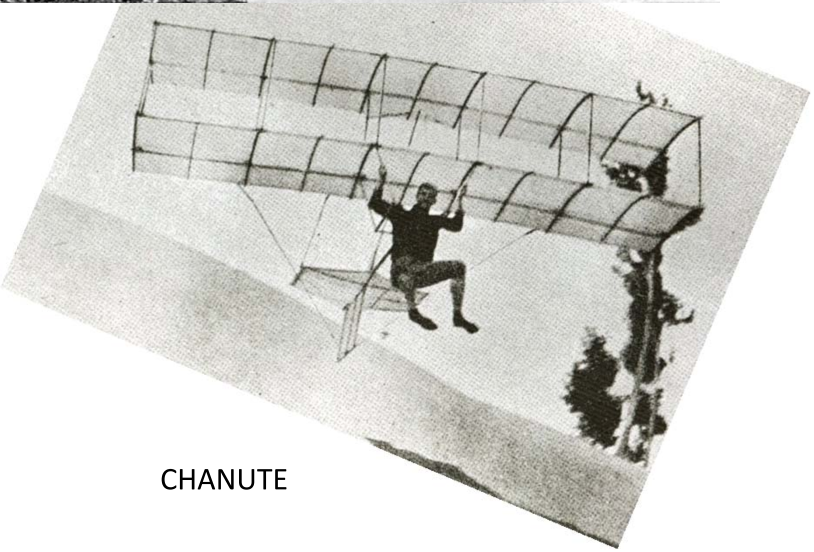
- ~220 AD: Kongming lanterns
- 1783: Manned balloons; Montgolfier (hot air) VS Jacques Charles (hydrogen)
- 1785: Blanchard crosses English Channel
- 1797-1860: Balloons used in French Revolutionary Wars and in US Civil War
- 1852:Dirigible; Henry Giffard
- 1890s: Alberto Santos-Dumont (speed, reliability, piston engines)

Gliders

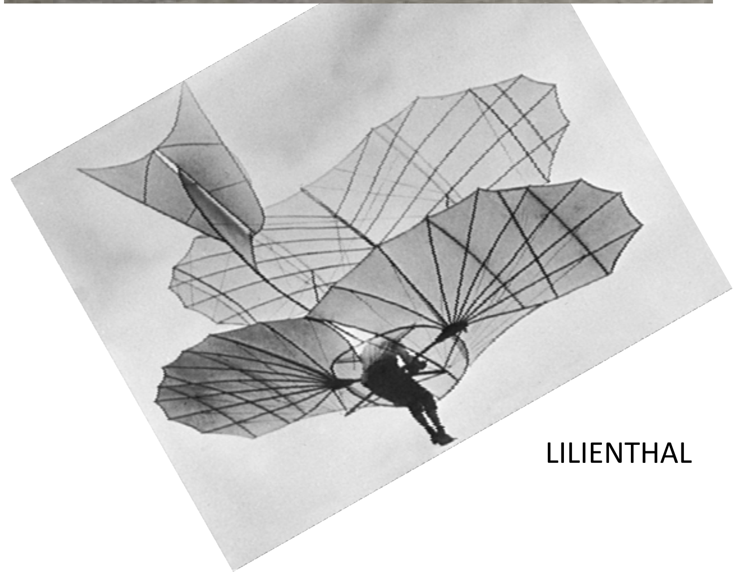
CAYLEY



MONTGOMERY



CHANUTE



LILIENTHAL

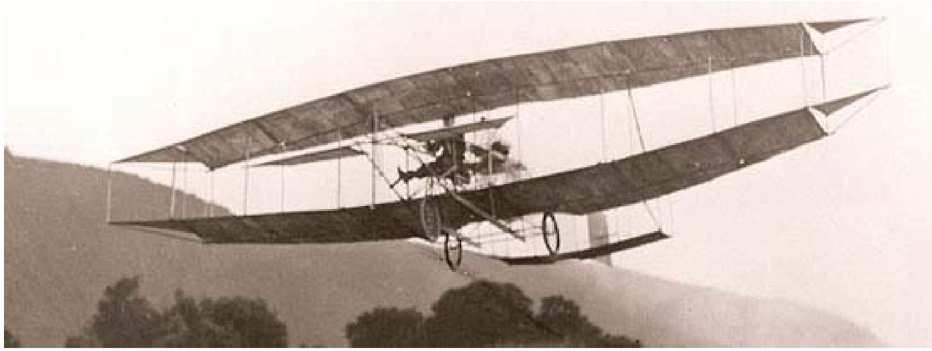
Gliders

- Same challenges as airplanes:
  Lift, controllability, stability, balance
- ~1800, George Cayley's key insight:
  Separate lift from thrust!
- ~1849-1853, Cayley: First manned gliders
- 1850-1900: Various gliders
  and unmanned powered models
- 1884: John J Montgomery: Long controlled glides
  in his "aero-plane", released from a balloon
- 1891: Otto Lilienthal starts gliding
- 1894: Octave Chanute's book
  (1896: Chanute's biplane glider)

Pioneers

WRIGHT FLYER

CURTISS JUNE BUG



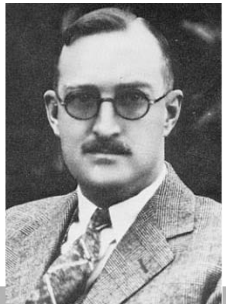
SANTOS DUMONT 14-BIS

BLERIOT 11

Pioneers

- Wright brothers, 1903: First sustained and controlled heavier-than-air flight. Three key technologies:
  - ***Lift***; Built their own wind tunnel, studied and improved upon Lilienthal's airfoils.
  - ***Power***; Developed the first quantitative methods to design, analyze, and optimize propellers (blades divided into sections, each analyzed as a small wing)
  - ***Controllability***; Elevator (pitch), rudder (yaw), wing-warping (roll)
- Alberto Santos-Dumont;
  1906: First flight to take off from level ground
  1907: Demoiselle plans published, many built worldwide
- Many French pioneers, 1907-'09: Voisin, Bleriot, Farman, Breguet…
- Blériot, 1909: crossed the English Channel
- Glenn Curtiss: June Bug (1908), won first air races (Reims, 1909), first airplane demonstrations to the military (1910), first takeoff and landing on a ship (1911), first seaplanes (1912), sold many airplanes worldwide, 1st real airplane "manufacturer".

Birth of an Industry

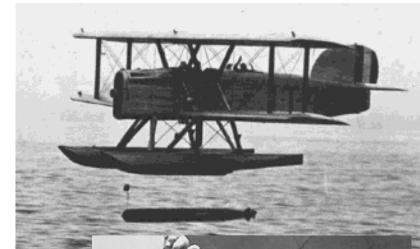


BILL
BOEING

B&W, 1916

MALCOLM
& ALLAN
LOCKHEED

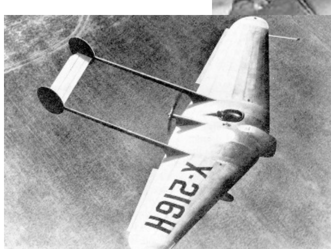
MODEL G,
1912



DT, 1921

DONALD
DOUGLAS

JACK
NORTHROP



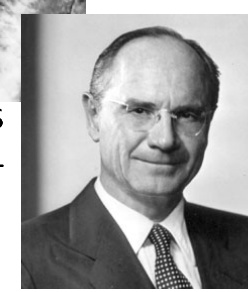
X-216H,
1929

LEROY
GRUMMAN

FF1, 1933

XP-67, 1944

JAMES
MCDONNELL

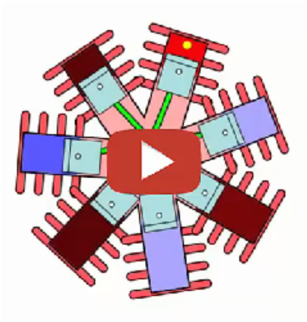


Birth of an Industry

- **Curtiss** and the **Wrights** were the first makers of powered airplanes in the US (1903, 1907). They eventually joined their companies and continued making engines and airplanes until the late 1940s (XF-87).
- A farmer in Kansas named Clyde **Cessna** was particularly impressed with Bleriot's crossing of the English Channel, built a replica of that airplane in 1911, and went about improving it.
- In San Francisco, brothers Allan and Malcolm and Victor Loughhead tried adding an engine to a Montgomery glider, then experimented on modifying a Curtiss airplane in 1912, before finally designing and building their own seaplanes (and changing the spelling of their name to **Lockheed**).
- To optimize their airplane structure, the Lockheeds hired architect Jack **Northrop**. He later left to work for other airplane companies, then started his own company but sold it shortly thereafter, and finally started one again in the 1940s to experiment with flying wings.
- Glenn **Martin** also started out by flying a Curtiss seaplane, and quickly decided he could design and built better ones, starting in 1912. In the 1930s, he designed some of the best seaplanes ever made. In the 1940s-50s, he struggled to make good jets once that technology came along, but then started making missiles and NASA rockets. Merged with Lockheed in 1995.
- One of Glenn Martin's early top engineers was Donald **Douglas**, who left in 1921 to start his own company (and also hired Jack Northrop).
- Bill **Boeing** bought an early Martin seaplane, damaged it, and found out it would take months for Martin to make repairs and replacement parts. Boeing decided it would be better if he just designed and built his own airplane. He did so in 1916.
- Meanwhile across the pond: Marcel **Dassault** designed some of the best propellers of World War 1, Louis **Breguet** played with aluminum structures and gyroplanes while developing and selling long-range biplanes, Anthony **Fokker** started making fighters, and Harry **Hawker** flight-tested Sopwith's fighters and eventually bought and renamed that company. Shortly after the war, Sergey **Ilyushin** left military service, studied aeronautical engineering, and designed gliders that won competitions around the world.
- Around 1930, the depression caused some bankruptcies and made assets like airplane factories relatively cheap for those who wanted to start airplane companies… such as Walter **Beech** (bought an old Cessna factory) and William **Piper** (bought the bankrupt Taylorcraft). Meanwhile, Loening Aircraft fired a bunch of their employees after being bought by Keystone Aircraft, and these employees started their own company, led by Leroy **Grumman.**
- In the late 1930s, many Russian aeronautical engineers were jailed on trumped up charges of sabotage, espionage and of aiding the Russian Fascist Party. Andrei **Tupolev** was among them. He designed the Tu-2 from jail, and was released so that he could lead a team to clone the B-29. Around the same time, Artem **Mikoyan** and Mikhail **Gurevich** started designing fighters together, designated "MiG".
- Jim **McDonnell** designed and flew an innovative fighter during World War 2 but failed to sell it. Right after the war, he proposed a jet fighter to the Navy, and created the first jet to land and take off from an aircraft carrier, and many many subsequent naval jets. (Merged with Douglas in 1967 and Boeing in 1997). Around the same time, a Soviet design bureau was formed to work on transport aircraft, led by Oleg **Antonov**. As for Pavel **Sukhoi**, he spent most of the 1930s and 40s trying to develop his own airplanes, but was not able to get them into production, and had to work for Tupolev and Ilyushin instead. But after the war, he was among the first to develop high-performance jets, which finally got him a production line once the Cold War got going.

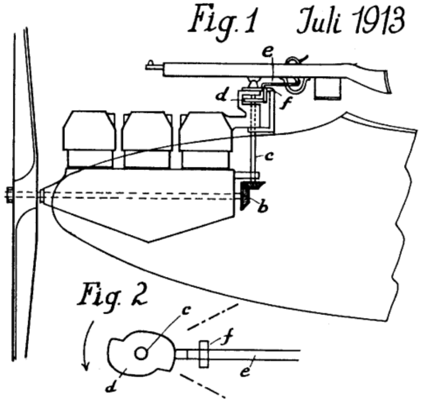
World War I

AIRCO DH1

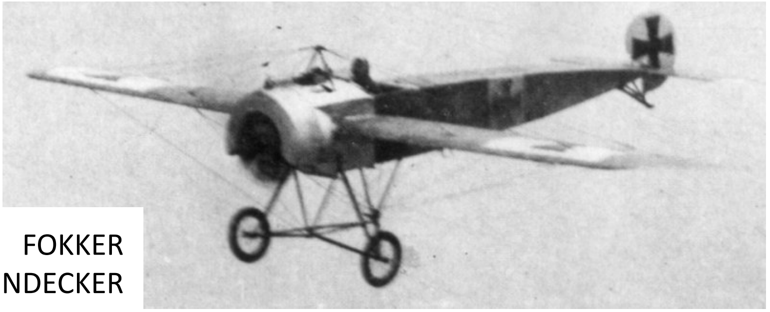


ROLAND GARROS

GOTHA G.4



ANTHONY FOKKER



FOKKER EINDECKER

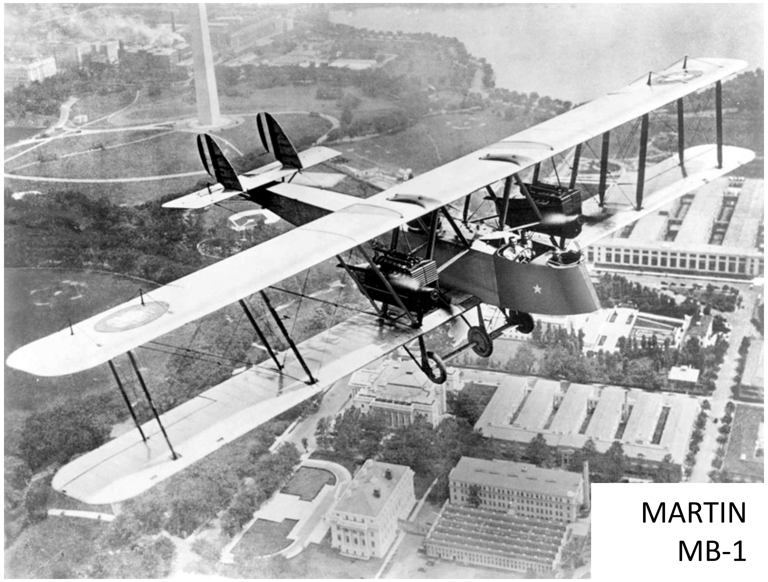
- The birth of air combat:
  - During the early months of the war, **airplanes were only for recon**. But before long (by the end of 1914), the armies got tired of operating under full view of the enemy! Gotta try to shoot those airplanes down!
  - This was initially approached like naval combat: Have one person “drive” the vehicle to match the speed and direction of the enemy (so that the enemy is not “moving around” in the gunsights), and have one or more other people aim and fire guns at the enemy. So early WW1 fighters had 1 to 3 gunners. **The pilot just tried to match the enemy’s speed and direction, to get close but not too close, stay in their guns’ blind spot, etc. The gunners did the shooting.**
  - Then, some people had a great idea. Roland Garros is credited with bugging Morane-Saulnier until they actually made it happen: **Have a gun that points forwards, and aim it by flying the airplane!** This allows for the airplane to only have to carry one person, improving speed, takeoff and climbing performance, agility, payload, etc.
  - How to fire through the propeller arc without breaking the blades? Some early WW1 airplanes had **pusher propellers** (in the back) which solved the problem: Breguet 4 & 5, DeHavilland 1 & 2, Royal Aircraft Factory F.E.2, Vickers F.B.5. Some airplanes had **tractor propellers with a small gunner “pulpit” in front** of it: SPAD A.2, Royal Aircraft Factory B.E.9 … but none of these were very good fighters: not extremely fast or agile.
  - Garros got a faster tractor airplane, a Morane-Saulnier Type L, and simply put **triangular deflector plates on the back of each prop blade** at the place where bullets would hit it. Each time a prop blade got in front of the gun, the bullets just bounced off. Garros became one of the first famously successful fighter pilots.
  - Fokker came up with an even better idea. (Others had patented it before, but he was the first to actually put it on operational aircraft): An **interrupter gear** that disengages the trigger for the fraction of a second when there is a propeller blade in front of the gun. His Eindeckers became the most deadly fighters in the first part of the War (see: the “Fokker Scourge”).
- How to cool the engine better, so that it can generate more power? Have a **radial engine**: All cylinders up front, being hit by fresh air. Even better, a **rotary engine**: The cylinders are bolted to the prop and all spin around, pushing on a driveshaft that is fixed to the firewall. Worked surprisingly well, but flung oil everywhere. (So pilots had to wear goggles, and scarves to wipe the oil off the goggles, hence the **“WW1 aviator” look**). Many of the best fighters in WW1 were powered by Gnome and LeRhone rotary engines: Sopwith Camel, Fokker Eindecker and Triplane, Nieuport 11, etc.
- Most airplanes had **thin airfoils** like those used by Lilienthal and the Wrights. Designers thought that **thicker airfoils** would be draggier. Fokker realized thicker airfoils are not draggier; At high speeds they’re actually better than high-camber thin airfoils, and are much stronger and stiffer due to extra height. This took a while to catch on. The prototype Fokker Triplane had cantilever wings, but pilots felt worried, so he added cosmetic braces for the wings to look more solid.
- **Bombing** was done mainly by Zeppelin, over cities, to hurt morale rather than destroy specific targets. Some airplane bombing was attempted, but was not very successful due to WW1 airplanes’ limited range and payload.
- Military aviation helped turn flying from an experimental / daredevil pursuit into a **systematized activity** with formalized training, maintenance, and other operational practices. Airplanes had to be reliable and easy to fly.

World War I

NIEUPORT 17

FOKKER D7

SOPWITH CAMEL



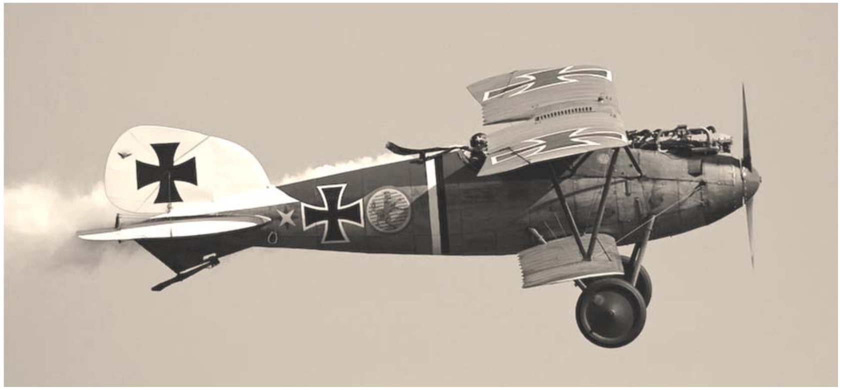
MARTIN MB-1

World War I

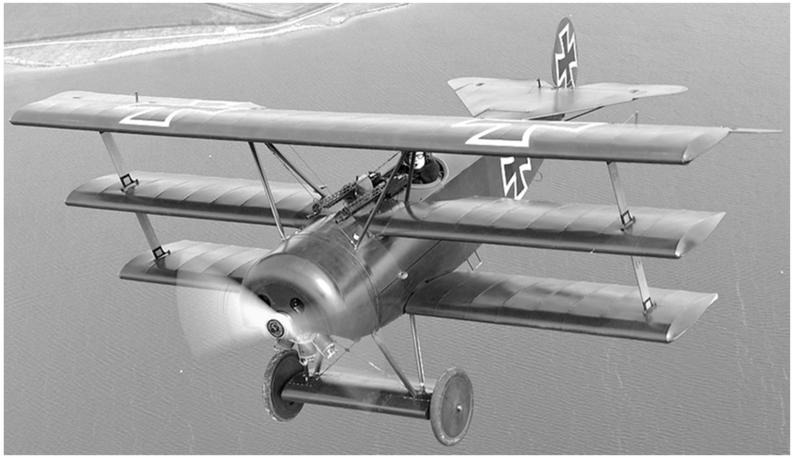
Eventually, this became the dominant configuration. Lots of exceptions (e.g. some monocoque fuselages, some steel beams and tubes, some cantilever wings, some monoplanes and triplanes, some pusher propellers, some engines between the wings) but most airplanes had…

- Externally-braced (with wires & struts) biplane wings
- Tractor engines (in the front), "V"/ in-line or radial or rotary
- Rudder and elevator and stabilizers in the back
- Truss-like structure, fabric-covered lattice of wooden beams and steel cables and (occasionally aluminum) brackets

World War I → The Golden Age



ALBATROS
(MONOCOQUE FUSELAGE)



FOKKER TRIPLANE
(THICK WINGS)

LOCKHEED VEGA

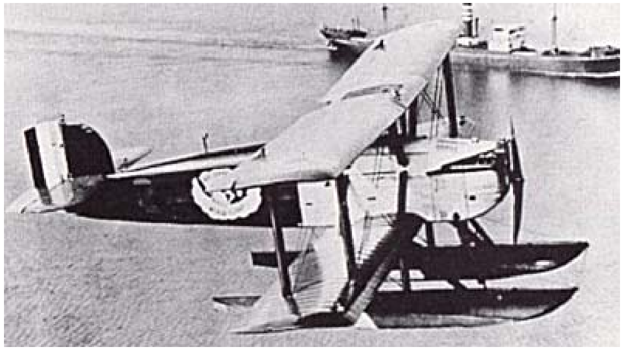
LOCKHEED SIRIUS

World War I → The Golden Age

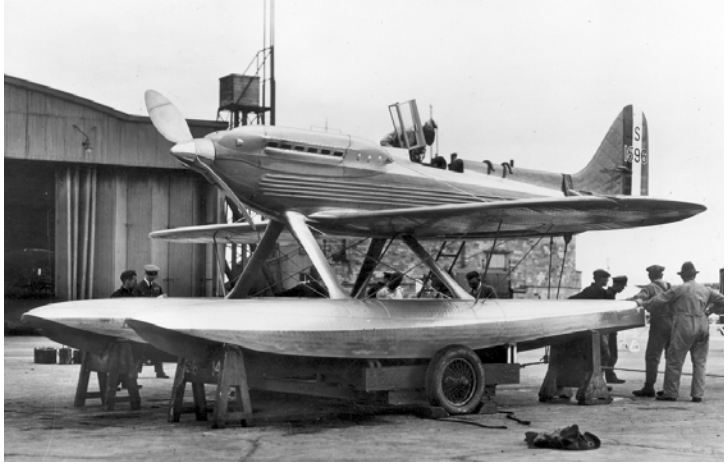
- Fokker-style thick wings prove stronger, stiffer, and no less aerodynamic than thin pre-War airfoils. Cantilever wings now practical.
- After raceplanes in 1911 and the Albatros fighter in WW1 tried monocoque construction (stiff and thick skin made of wood to carry all loads, like a boat hull, instead of a truss lattice), the Lockheed brothers finally master it in the late 1920s. Lighter overall, more aerodynamic, and more room inside.

The Golden Age

DOUGLAS WORLD CRUISER



SUPERMARINE SCHNEIDER RACER



CHARLES LINDBERGH

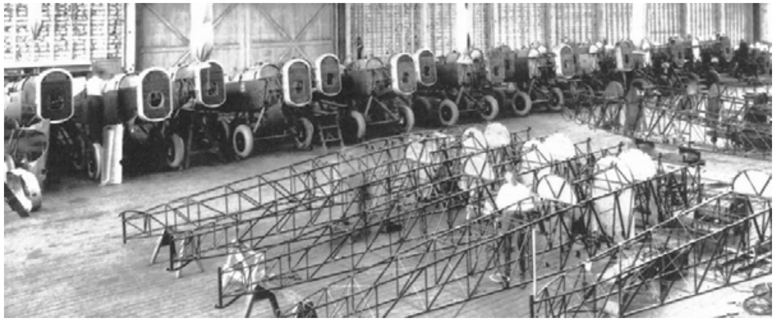
ELREY JEPPESEN

The Golden Age

- Douglas flight around the world
- Air mail, Jeppesen charts/networks
- Speed record broken about twice a year, altitude records about once every two years
- Technology pushed by air races (e.g. Schneider Trophy), prizes (e.g. Orteig Prize), the military, and airplane and engine manufacturers
- Awards: Harmon Trophy, Collier Trophy, Wright Brothers Medal…

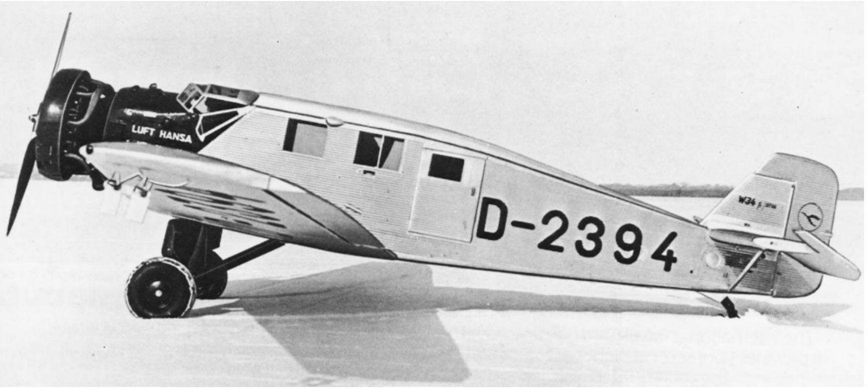
The Golden Age

BOEING REPLACES "PONY EXPRESS" DH-4 STRUCTURE WITH METAL



PACKARD LePERE LUSAC 11 (40,000 feet!)

JUNKERS W34



METAL LOCKHEED VEGA

The Golden Age

- 1920s: Metal starts replacing wood in truss lattice structures. (Boeing re-built many WW1 bombers, replacing wood with metal).
- 1930s: Aluminum is cheap enough to build an entire airplane out of, using stiffened panels rather than thick wood. This allows for bigger airplanes. (So wooden monocoque airplanes were only dominant for a brief period in the late 1920s).
- Innovations such as turbochargers and superchargers allow for more powerful engines, and for faster and heavier airplanes.

The Golden Age

BOEING 80

FOKKER F.VII

JUNKERS 52

SPARTAN CRUISER

FORD TRIMOTOR

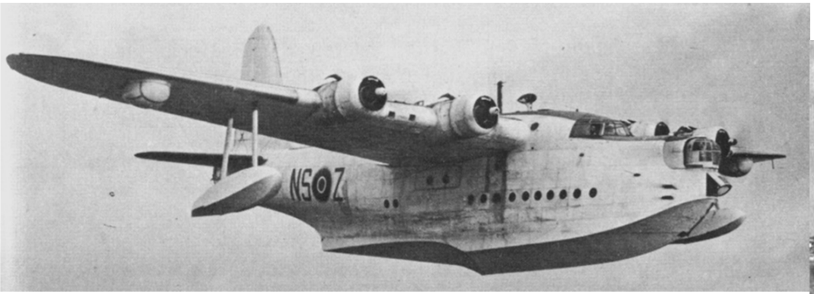
STINSON "A"

The Golden Age

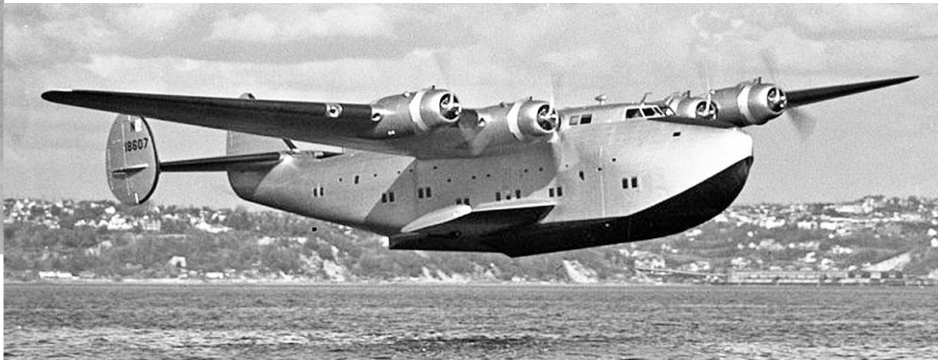
- Late 1920s radial engines were relatively small.
- Larger radial engines are harder to cool.
- Smaller radial engines can operate at higher RPMs without the propeller going supersonic. Higher RPM = more horsepower for their weight.
- More smaller engines means more redundancy in case of engine failure.
- For all these reasons, many of the first large transports in the late 1920s and early 1930s were trimotors, with three relatively small engines.

The Golden Age

SHORT SUNDERLAND



BOEING 314

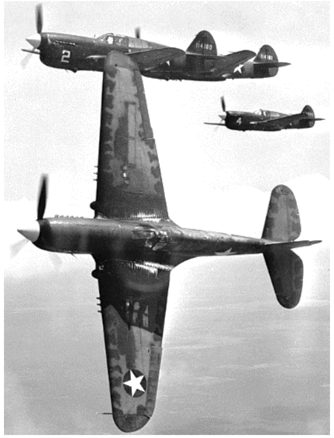


DOUGLAS
C-47 / DC-3

The Golden Age

- Large, fast airplanes need long runways to take off… except seaplanes. Many large seaplane airliners in the early 1930s.
- Then Douglas developed the DC-3, a major boost to commercial aviation. Very modern airplane: all-metal, retractable gear, reliable, could fly high and fast and far (for the time), didn't need lots of runway… Most importantly: Could pay for its own operations by selling tickets alone, no need for government subsidies or carrying mail. Anyone who could get their hands on a DC-3 could start a profitable airline. Suddenly, in 1935, air travel transitioned from "adventurous" to "reliable" and – finally, and most importantly – to "profitable". The DC-3 is said to be the second most important airplane in aviation history (after the Wright Flyer).

World War II

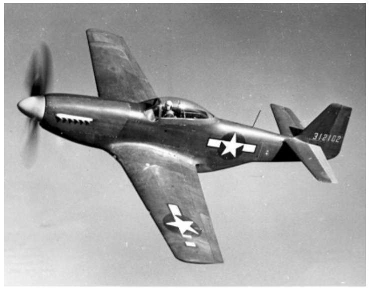


P-40
(1938)
1150 hp
240 miles
29,000 feet

B-17
(1935)
4X 1200 hp
2000 miles
35,000 feet

Wildcat
(1937)
1200 hp

Spitfire Mk 1
(1938)
1030 hp



P-51D
(1943)
1720 hp
1155 miles
42,000 feet

B-29
(1942)
4X 2200 hp
3250 miles
47,900 feet

Bearcat
(1944)
2250 hp

Spitfire Mk 24
(1943)
2120 hp

World War II

- Most airplanes at the end of the War did not look very different from most airplanes at the beginning. Advances were subtle, but important.
- Much more horsepower and greater altitudes thanks to better technology in piston engines, e.g. turbochargers.
- Better efficiency (payload, range) thanks to better engines and cleaner aerodynamics, e.g. laminar flow
- As airplanes became able to fly higher, pilots became the altitude-limiting factor. So… pressurization!
- Better weapons accuracy thanks to reflector sights, gyro gunsights, radar gunsights, and computationally advanced tachymetric (surveying) bombsights

World War II

ME 163

HORTEN 229

V1

P 1101

ME 262

V2

JUNKERS 287

World War II

Allies making evolutionary changes,

Nazis exploring revolutionary changes:

- Jet engines
- Rocket engines
- Cruise missiles
- Tail-less configurations, swept wings, forward-swept wings, flying wings, variable-geometry wings!

Jet Age – Bombers

DOUGLAS YB-43

NORTH AMERICAN B-45

CONVAIR XB-46

MARTIN XB-48

NORTHROP YB-49

BOEING
B-47

MARTIN XB-51

Jet Age – Bombers

- After the war, there was time (and resources due to the Cold War) for experimentation. Tremendous advances in aeronautical technology.
- What is the optimal configuration for a large jet plane?
- USAF orders prototype jet bombers from all the major manufacturers in the late 1940s.
- One of these far outperformed the others, and became the blueprint for all future large jets. (Can you guess which one?)
- B-47 key features: Thin wings, 35° of sweep, yaw damper, spoilers for roll, jet engines in under-wing pods, air inlets under and just forwards of the leading edge.

- (Of course, the YB-49's configuration would make a comeback 40 years later, after stealth and fly-by-wire were figured out, making it desirable and practical).

Jet Age – Fighters and X-Planes

F-80 (1944)

F-86 (1947)

F-104 (1954)

F-4 (1958)

X-1 (1947)

D-558-2 (1948)

X-2 (1956)

X-15 (1959)

Jet Age – Fighters and X-Planes

- Nazis and the UK had jet engines in the 1930s, but jets could not fly exceptionally fast: Messerschmitt 262, Meteor, XP-59, not much faster than the fastest piston-powered airplanes. The main reason was realized around 1944: These early jets did not have thinner wings.
- USAF & Navy order prototype jet fighters from all major manufacturers in late 1940s.
- First “batch”, with straight wings: F-80, FH1, F-84, F9F… Entered service and set speed and altitude records. F-80 could almost break the sound barrier.
- F-86 Sabre / FJ Fury showed superiority of swept wings. On its first flight in 1947, it became the first airplane to break the sound barrier! (but could only do so in a dive).
- Soon, other fighters got swept wings too: F-90, F-84F, F-9…
- Lots of experimentation with new aerodynamic configurations, new engines, afterburners, rockets, better materials… Series of “X planes” (*The Right Stuff*, “edge of the envelope”…). As in the 1920s/30s, altitude and speed records were broken often: Mach 1 (1947), 60,000 feet (1948), Mach 2 and 80,000 feet (1953), Mach 3 and 100,000 feet (1956).
- By 1960: F-4 Phantom (basically a modern fighter), Lockheed Blackbird (still the fastest jet ever), X-15 (300,000 feet and Mach 6.7, transitioned from “aircraft” to “spacecraft” and back).
- Key developments in weapons: better radar, radar gunsights, heat-seeking missiles, radar-guided missiles…
- One big problem: These early jets were gas-guzzlers. Very limited range, especially small fighters..
  - Boeing developed the aerial refueling boom in the late 1940s to address this.
  - However, with no large jets in existence, 1950 tankers were slow prop planes.
  - Faster jets in the early-mid ‘50s had trouble flying slowly enough to refuel from them.
  - If only Boeing made a jet tanker…

Jet Age – Airliners

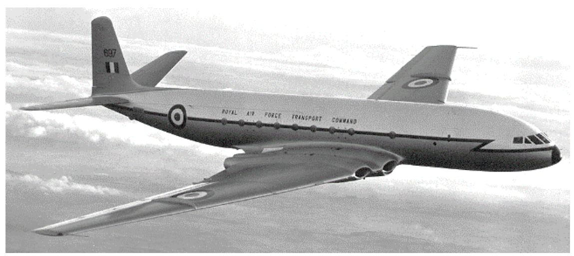

CONVAIR 240


LOCKHEED L188 ELECTRA


VICKERS VISCOUNT


BRISTOL BRITANNIA

DEHAVILLAND COMET



AVRO CANADA C102

DOUGLAS DC-8


VICKERS VIKING


BOEING 707

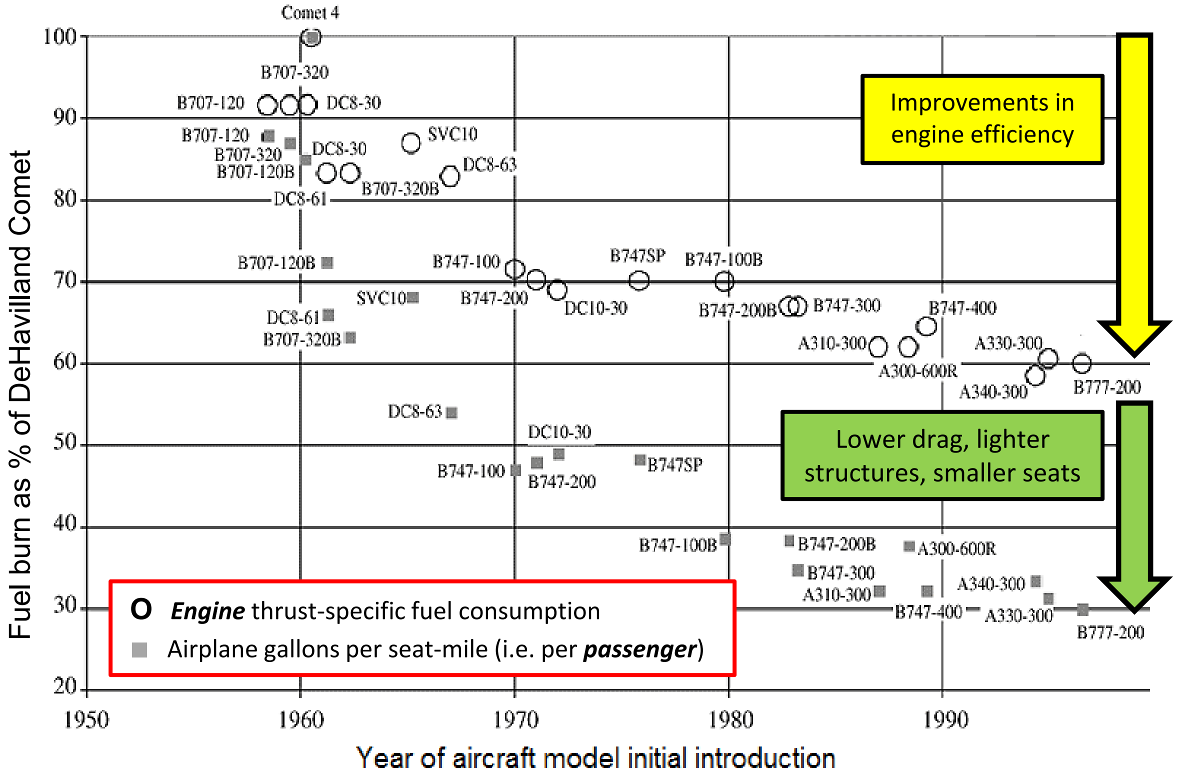

CONVAIR 880

Jet Age – Airliners

- Airlines still wanted turboprops. Jets were an unknown: Reliability? Fuel efficiency? Safety of high flight?
- Jetliners were only tried in tiny numbers until ~1955. Early jetliners (Viking, Comet, C102) were not great performers, sold poorly. The Comet accidents didn't help.
- Boeing's B-47 data was impressive; Boeing knew that a new, B-47-like jetliner would be a great airplane. Coincidentally, this hypothetical new airplane would have nearly identical specs to the new jet tanker needed by the USAF… so Boeing developed the 707. Once they demonstrated it, there was huge demand. Other manufacturers quickly developed clones.

Fun story: Some of the funds for 707 development were supplied by the USAF, for developing a tanker that could keep up with the fast new fighters. But most of the cash came from Boeing profits that would be otherwise paid to the US government anyways, due to an "Excess Profits Tax" against war profiteering: Profits during wartime [e.g. early 1950s, Korean War] in excess of profits during peacetime [e.g. late 1940s] were taxed at 82%! And Boeing had had a slump in the late 1940s, almost no profit, trying to sell souped-up B-29s (e.g. 377, B-50). So nearly all Boeing profits in the early 1950s, e.g. from the B-47, would go to Uncle Sam… unless it went into R&D, because R&D costs were subtracted from taxable profits. Boeing CEO Bill Allen was a tax attorney, realized all this in the 1950 to 1953 period, and dedicated most of Boeing's profits – about 25% of the value of the company – towards developing the 707. (He had been wanting to develop a jetliner since 1947 when B-47 performance data started to come in, but at the time, Boeing could not have afforded it).

Fuel Efficiency



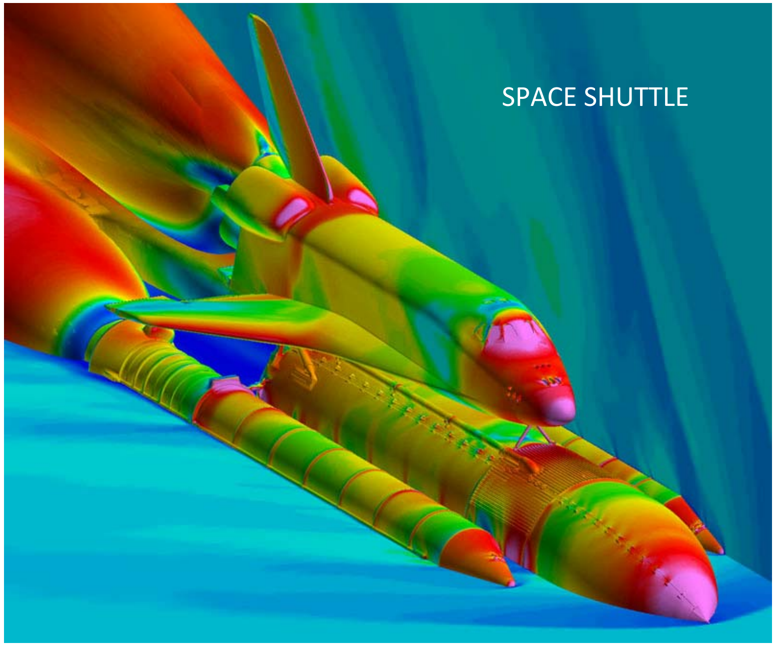
Fuel Efficiency

- Until ~1970, air travel was only for the “jet set”
- Airlines competed on speed and range, not on efficiency
- This “maxed out” in the 1960s. How to compete on price?
- The USAF wanted a large transport. Boeing and Lockheed studied what an extra-large airplane would look like. P&W and GE studied how high-bypass (i.e. wide) turbofan jet engines would allow for a long-range large transport, by delivering much more thrust while not burning much more fuel. The USAF chose Lockheed and GE. The result: The C-5.
- Boeing used some of the knowledge from this study, and the engines P&W developed , to create the 747. By far the most fuel-efficient airplane in existence. Trip cost per passenger per mile was drastically reduced.
- It turns out that many more people will want to travel by air when tickets are cheaper! Higher fuel efficiency from wide turbofans caused huge increase in air travel. (~1 million flights per year in 1960 in jetliners in the US, now more like ~20 million flights per year).

727-200	**30** MPG per seat
707-320B	**34** MPG per seat
737-600	**52** MPG per seat
767-200ER	**73** MPG per seat
777-200ER	**81** MPG per seat
787-8	**88** MPG per seat
787-9	**102** MPG per seat

Sources:
planes.axlegeeks.com
wikipedia.org/wiki/Fuel_economy_in_aircraft

Computers & Composites



Computers & Composites

Nearly all airliners since the 747 use wide turbofans.
(Newer airliners use even ***wider*** turbofans!)

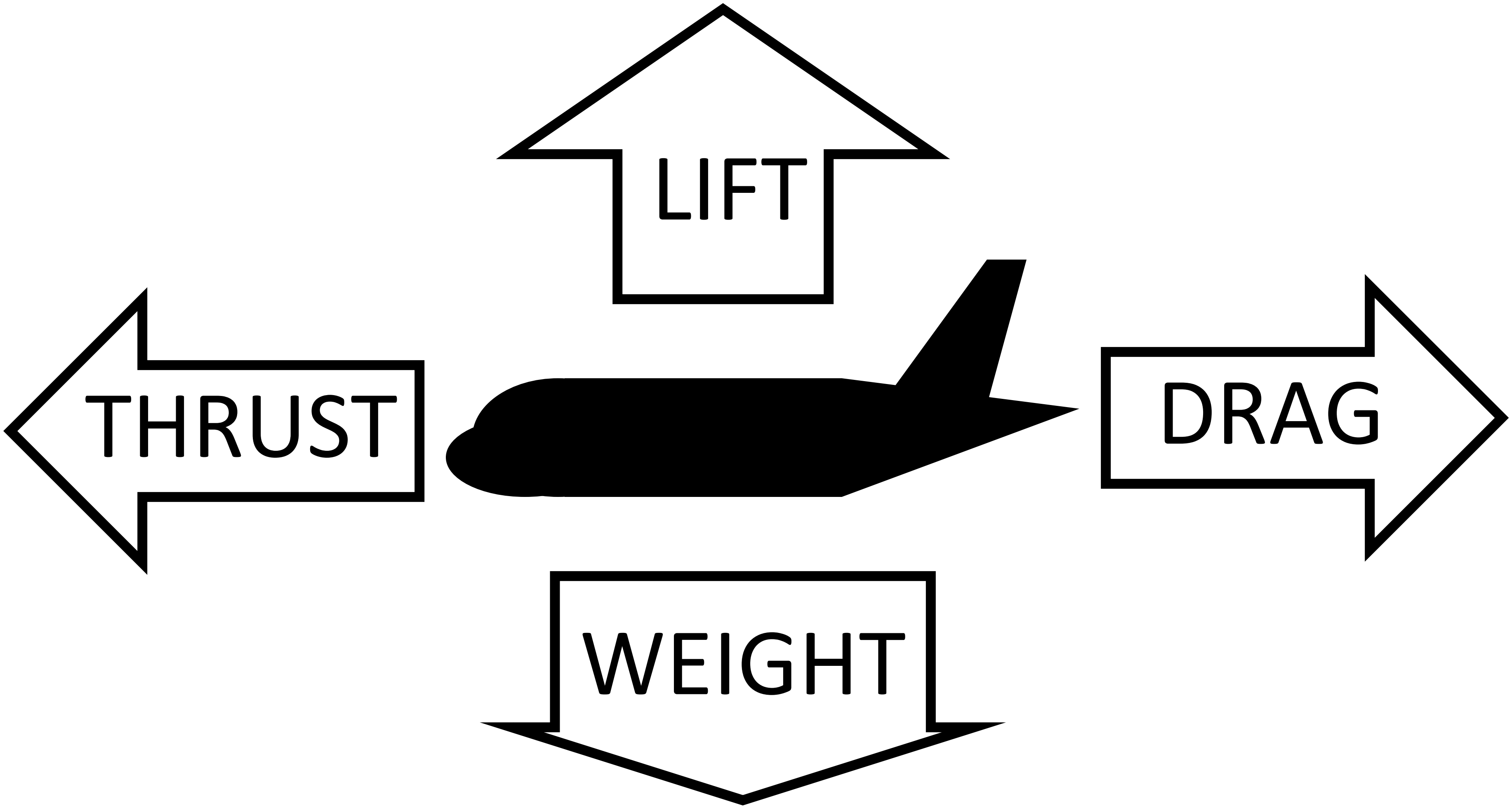
Other technologies also lower fuel burn and other costs:

- Wingtip devices
- Lighter materials (better alloys, and composites)

Computers:

- More efficient logistics (airport operations)
- More efficient flying (climb, cruise, navigation…)
- More efficient controls (fly-by-wire, load alleviation)
- Cheaper and better component design and manufacturing
- Not just for airliners: Fighters, spacecraft, etc.

Four Forces



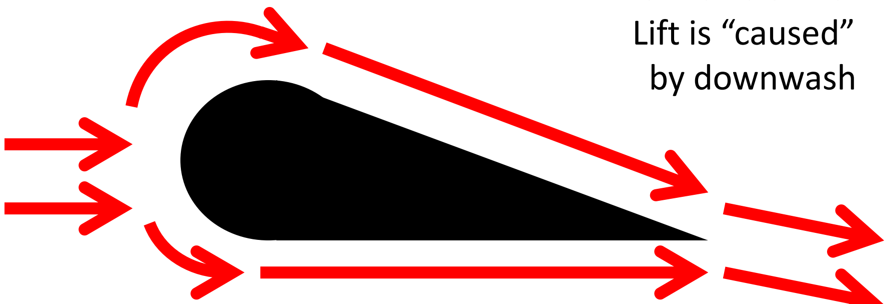
Four Forces

- ***Lift*** is the upwards force from how the wings push the air downwards
- ***Drag*** is the backwards force from how everything on the airplane pulls the air forwards
- ***Thrust*** is the forwards force from how the engines push the air backwards
- ***Weight*** is the downwards force from how the airplane and the Earth attract each other

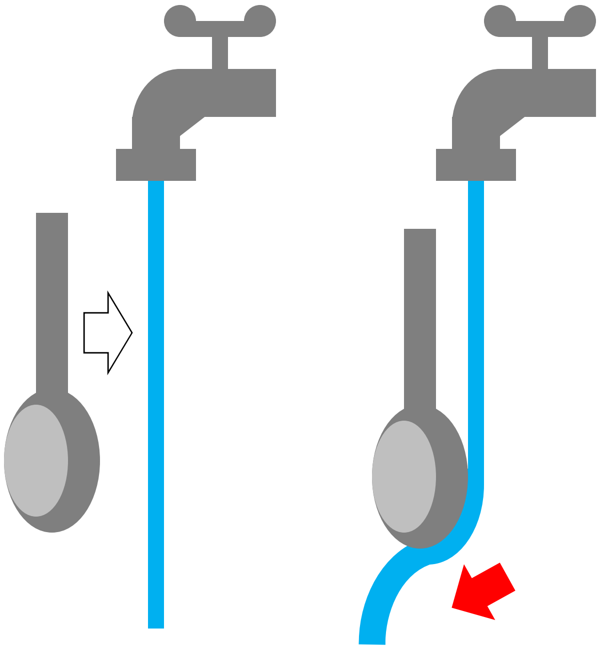
(Now, let's break down what causes these four forces.
How can we reduce Weight & Drag, and
more efficiently generate Lift & Thrust?)

Lift and Wings

Newton's 3rd Law:
Lift is "caused"
by downwash



Coanda effect
at the kitchen sink:
Fluids follow
curved surfaces



Lift and Wings

- Newton's Third Law: Wings deflect air downwards, air pushes wings upwards.
- Air is deflected downwards because it follows the curvature of the wing: This is the "Coanda effect", like the convex side of a spoon deflecting a thin stream of water from a faucet.
- In short: **How do wings work? They deflect air downwards, which makes the air push them upwards.** This is the key. Everything else is details.

Wings Deflect Air Downwards

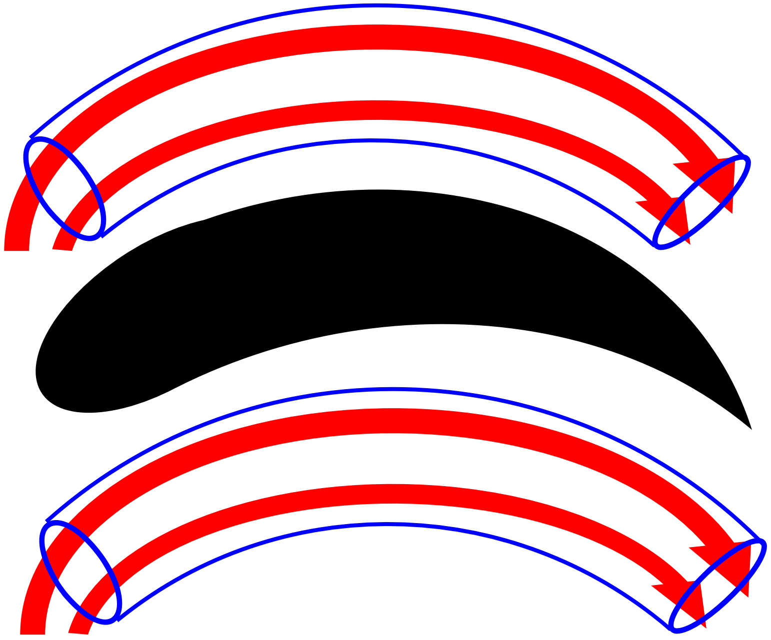
Wings Deflect Air Downwards

- As an airplane passes by, it pulls the air above it downwards, and pushes the air below it downwards. (This is visible if there are clouds nearby).
  This is called the downwash, the "equal and opposite reaction" to making upwards lift.
- The downwash is an unavoidable part of making lift; they are inseparable. (In order for a car or bike to push itself forwards, the wheels must push the road towards the back. In order to swim or row forwards, you must push some water towards the back. Same thing here: To make upwards lift, the wings must push air downwards).

HOW do wings deflect air downwards?

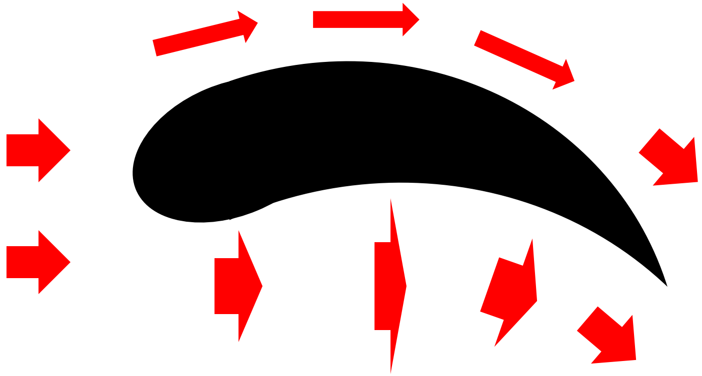
Curved Airfoil (Euler Equations):

Air along top of wing is "on the inside of a turn":
Pressure drops due to centripetal effect.
Air along bottom of wing is "on the outside of a turn":
Pressure rises due to centrifugal effect.



Cambered Airfoil (Bernoulli Principle):

Air along top has a narrower path, speeds up, pressure drops.
Air along bottom has a wider path, slows down, pressure rises.



HOW do wings deflect air downwards?

- How does the wing exert a downwards force on the air?
  How does the air exert an upwards force on the wing?
- Well**, the air pressure under the bottom of the wing must be relatively high,** and **the air pressure over the top of the wing must be relatively low.**
- How does this happen? Two explanations:
- (1) One explanation comes from the fact that the air is turning as it flows over and under the wings. In order for *anything* to make a turn, it must be pulled from the inside and/or pushed from the outside.
- According to the **Euler Equations for fluid mechanics**, if a fluid (e.g. water or air) is flowing in a pipe and the pipe makes a turn, then the pressure on the "outside" of the turn goes up, and the pressure on the "inside" of the turn goes down. (This is intuitive, from a centripetal/centrifugal point of view).
- So over the top, the air is on the inside of the turn, being pulled down by the wing (and thus "pulling up" on the wing) with low pressure… and under the bottom, the air is on the outside of the turn, being pushed down by the wing (and thus pushing up on the wing) with high pressure.
- (2) The more commonly-given explanation: Due to camber (wing is convex on top and sometimes concave on bottom), air over the top of the wing has a "constricted" path and accelerates (same flow rate ÷ less room = more speed, like river rapids). Air under cambered wings has a "widened" path and slows down.
- Bernoulli's principle (see next slide) basically says that the energy in the air flowing around an airplane can be converted between speed and pressure.
  Less speed = more pressure, and vice versa.
- So the air over the wing speeds up and loses pressure, and the air under the wing slows down and gains pressure.

Bernoulli's Principle

$$P \quad + \quad \tfrac{1}{2}\rho V^2 \quad = \quad P_0 = (H-z)\rho g$$

"Static pressure" + **"Dynamic pressure"** = **"Total pressure"**

"Static pressure"
The air pressure
at some given spot
around an airplane

"Dynamic pressure"
The energy in the air
in the form of speed
at that spot, somewhere
around an airplane

"Total pressure"
a.k.a "**Ram pressure**"
The total energy in the air
(<u>a constant</u> everywhere
around an airplane
at any one moment)

Bernoulli's Principle

- Bernoulli's principle basically says that the energy in the air flowing around an airplane can be converted between speed and pressure.
- If the airplane is going at a certain speed through air of a certain density, then each bit of air going by the airplane has a certain amount of "total" energy. Some of that energy is in the form of speed (i.e. the speed of the air going past the airplane). Some of that energy is in the form of pressure (i.e. the air pressure that you could measure with a barometer, that property that makes your ears pop when it changes too fast).
- **In regions around the airplane where the air is slowed down (e.g. right in front of vertical things like the tip of the nose or the leading edges of the wings and tail fins), the pressure goes up.**
- **In regions around the airplane where the air is sped up (e.g. over the tops of the wings and the undersides of the horizontal tail fins), the pressure goes down. This is how most lift is generated.**
- Note that Bernoulli assumes that no energy is given to, or taken from, the air in question. A propeller adds energy to the air: Air downstream from the propeller has more speed AND more pressure than the incoming air. Something sticking out of the airplane, like an antenna or a missile, takes energy: The air downstream of the thing sticking out might have less pressure AND less energy than the incoming air in front of the airplane. So Bernoulli applies most accurately to air that is at least a fraction of an inch off the airplane, that does not actually touch the airplane. (Later, we'll discuss viscosity and "boundary layer air".)
- The equation is in units of pressure.
- The **"static pressure"** is just the air pressure (what you'd measure if you used a barometer).
- The **"dynamic pressure"** is the energy that is in the form of air speed (i.e. not actually pressure). If the air were slowed down, the dynamic pressure equation tells you how much more actual pressure you would get out of air that has that speed and that density. In other words,
  " $\frac{1}{2}\rho v^2$" converts the air speed into the extra pressure you would get if you slowed the air down.
- The "total pressure" or "ram pressure" is the highest pressure that you could possibly experience on the outside of an airplane if you slowed the air all the way down to zero speed relative to the airplane (while flying at a certain speed through air of a certain density). In other words, it is the static pressure (the actual air pressure far from the influence of the airplane) plus the dynamic pressure (the "extra pressure" that, at the moment, is actually in the form of speed, not pressure, but that would cause air pressure to increase if the air was slowed to a stop).
- When you stick your hand out the car window, if you make it flat and perpendicular to the airflow (trying to "stop" the air), you feel the air push your palm. That's because air is slowing down in front of your palm, so some of the speed is being converted to pressure (i.e. less dynamic pressure, which is just speed, and more static pressure).

Dynamic Pressure

$$P + \boxed{\tfrac{1}{2}\rho V^2} = P_0 = (H-z)\rho g$$

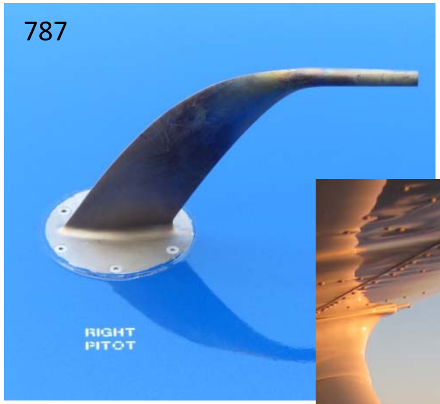
"Static pressure" + **"Dynamic pressure"** = **"Total pressure"**

"Static pressure": The air pressure at some given spot around an airplane

"Dynamic pressure": The energy in the air in the form of speed at that spot, somewhere around an airplane

"Total pressure" a.k.a **"Ram pressure"**: The total energy in the air (a constant everywhere around an airplane at any one moment)

PITOT TUBES:



Dynamic Pressure

- **Question**: You're driving at 25mph. You stick your hand out the window and feel pressure from the air. If you were driving at 50mph, how much stronger would that pressure feel on your hand?
- **Question**: You're driving at 25mph near sea level. You stick your hand out the window and feel pressure from the air. If you were driving 25mph on a road in Denver (5,000 feet high, where the air is less dense), you feel a lower pressure. How much weaker would the pressure be?
- **Question**: How much faster would you have to drive in Denver to get the same pressure on your hand that you got at sea level at 25mph?
- **Question**: Near sea level, an airplane near its max angle of attack can safely fly at 50mph without stalling, so it lands at 50mph. But, if landing at an airport at 14,000 feet, how much faster does the airplane need to fly in order to generate enough lift to stay up in the air?
- **Question**: While generating a certain amount of thrust in its engines, a certain jet has a maximum speed at sea level of 450mph. Up at 33,000 feet where the air is less dense, that jet's engines can still generate that same amount of thrust. How much faster will the jet be able to fly?

Dynamic pressure is one of the most important principles in aeronautical engineering.
It is the concept that makes it possible to answer questions like the ones above.

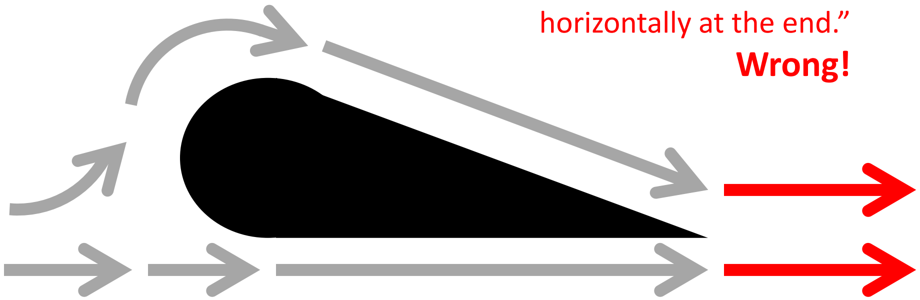
- When the speed is doubled, if all else stays the same (i.e. same air density, airplane going through the air at same angle/orientation), aerodynamic forces go up four times. This means both lift and drag. Triple the speed, and the forces go up by a factor of 9. (So to go 2x faster, an airplane might need ~4x as much thrust. But going twice as fast means a wing can generate 4x as much lift and pull 4x as many Gs, structural strength permitting).
- When air density goes down by 50% (e.g. go up to 22,000 feet), aerodynamic forces (at the same speed) go down to 50%. When air density goes down by 66% (~33K feet), aerodynamic forces (at the same speed) go down by 66%. So while flying higher, an airplane needs to fly faster (or at a higher angle of attack) to stay up in the air.
- When speed decreases (and thus dynamic pressure decreases by the square of the decrease in speed), in order to generate enough lift to keep the airplane in the air, a wing must fly through the air at a greater angle of attack, which increases the wing's coefficient of lift. More about this, starting in slide 68.
- How do airplanes measure their speed through the air? A ***pitot tube***. The tip measures the ram pressure (like your hand sticking out the car window), and a hole on the side measures the air pressure (like a barometer). The difference between them is the dynamic pressure, which is $\frac{1}{2}\rho V^2$, so **$V=\sqrt{\text{pitot tube pressure difference} \div \frac{1}{2}\rho}$**
- For "ρ", the calculation done by the airspeed indicator and the pitot tube uses the sea-level density, which is higher than the density at altitude. This means that, while going at the same true speed, a pitot tube will indicate a lower speed at higher altitudes. This is OK, because this "indicated" airspeed (which is directly related to dynamic pressure, but only indirectly related to the actual speed through the air) is what determines all aerodynamic forces and thus an airplane's capabilities (e.g. when it will stall, how many Gs it can pull, whether it's OK to lower the gear and flaps, etc.). Also, this is why airplanes can fly faster at higher altitudes while generating the same amount of thrust: Lower density and higher speed give the same dynamic pressure and thus the same aerodynamic forces as flying lower and slower. So at some power setting, an airplane may see the same indicated airspeed at a variety of altitudes, while in reality it will actually be flying faster while at higher altitudes.
- Another neat use of the Bernoulli principle: If there is an opening in a pressurized container (e.g. a bucket of water with a hole in it, a spray can, a water gun, a party balloon, a fire hydrant, a whoopee cushion, a deflating air mattress, etc.), how fast does the fluid come out of the opening? Subtract the atmospheric pressure (P) from the container's internal pressure just inside the opening (Po); You get the dynamic pressure. If you know the density of the fluid, divide that (and ½) out of the dynamic pressure, take the square root, and you get the fluid speed that corresponds to that difference in pressure.

Lift – Two Myths

MYTH:

"As the airflow goes around the wing, local changes in pressure will generate lift, even if the air exits horizontally at the end."

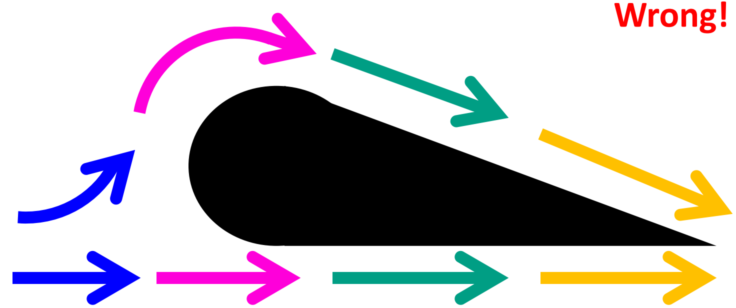
Wrong!



MYTH:

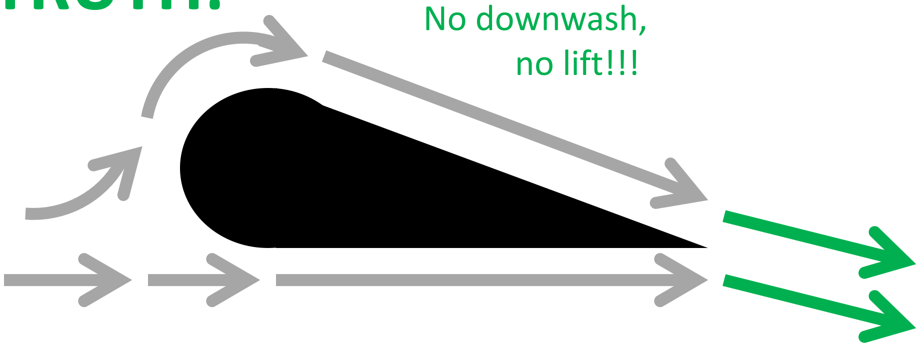
"The air over the top speeds up because it has to get to the back of the wing at the same time as the air under the bottom and come back together with it."

Wrong!



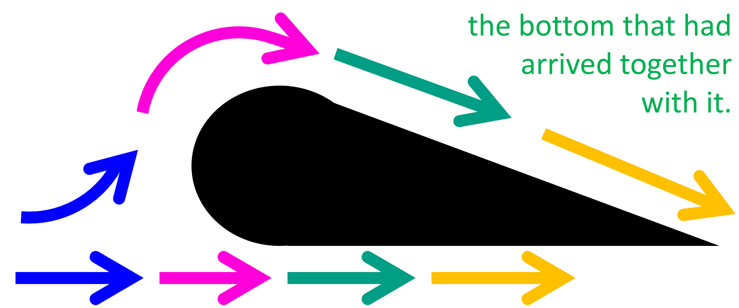
TRUTH:

No downwash,
no lift!!!



TRUTH:

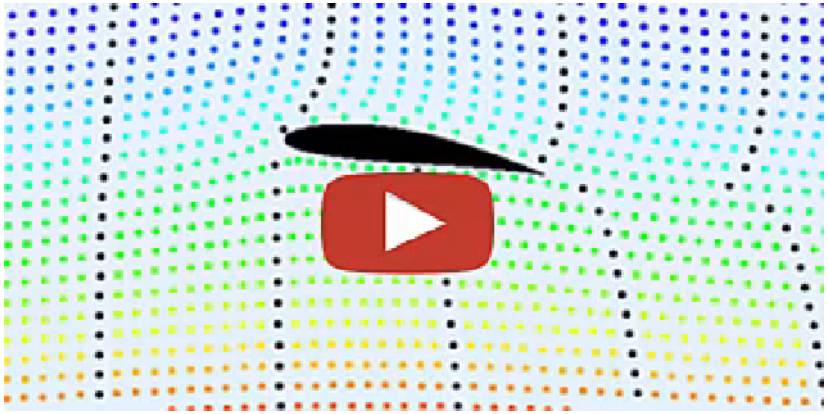
The air over the top actually gets to the trailing edge BEFORE the air under the bottom that had arrived together with it.



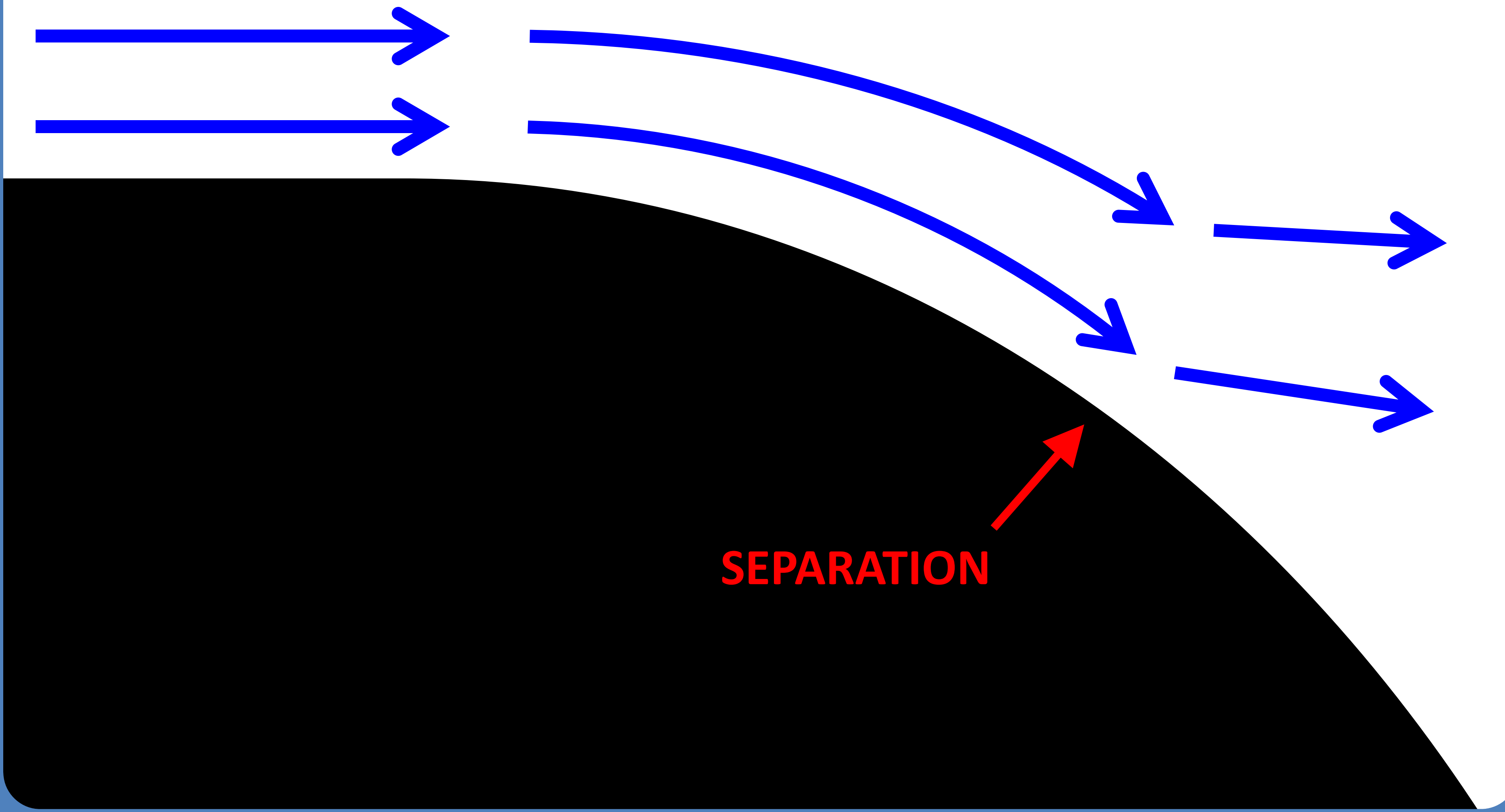
Lift – Two Myths

- The downwash off the back of the wing is absolutely essential for lift. The wing only gets pushed up if the air gets deflected down! If a diagram shows "airflow" going around a wing but then continuing on horizontally (not downwards) past the trailing edge, then this diagram completely missed the point. (Unfortunately such diagrams can be found in many "authoritative" sources).

- The air over the top does not have to get to the trailing edge at the same time as the air under the bottom. In fact, **the air over the top gets to the trailing edge BEFORE the air under the bottom:**



The Limits of Coanda: Flow Separation



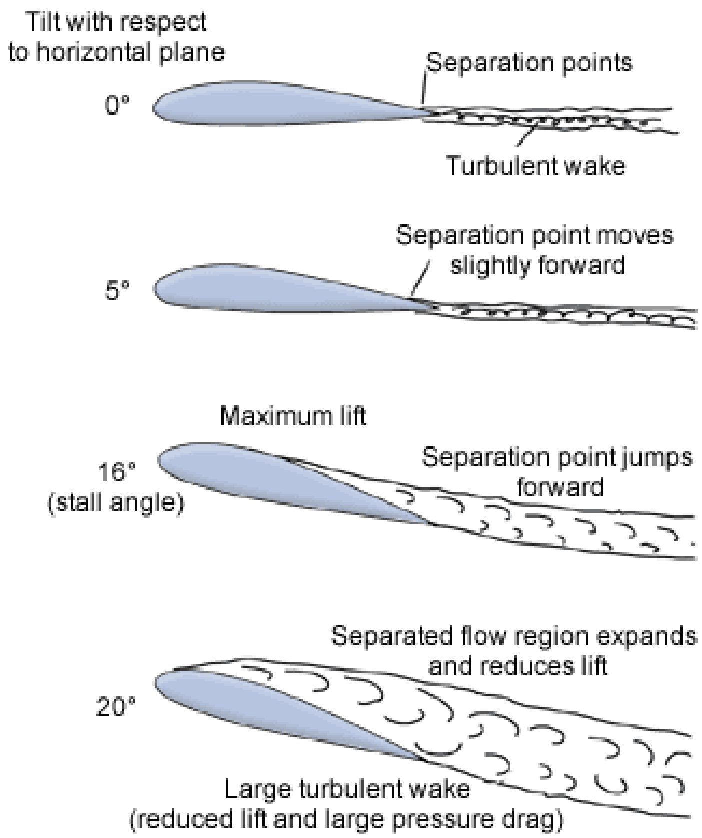
The Limits of Coanda: Flow Separation

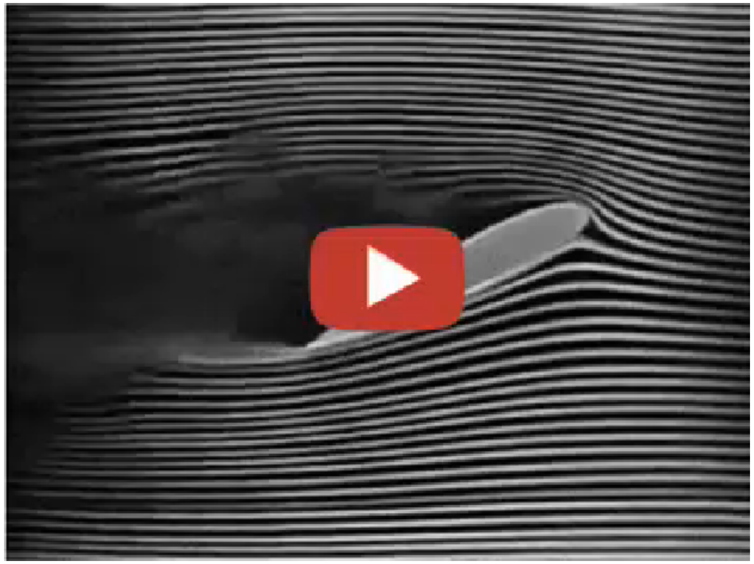
Fluid flow tends to follow a surface…
unless, and until, the surface curves away too steeply.

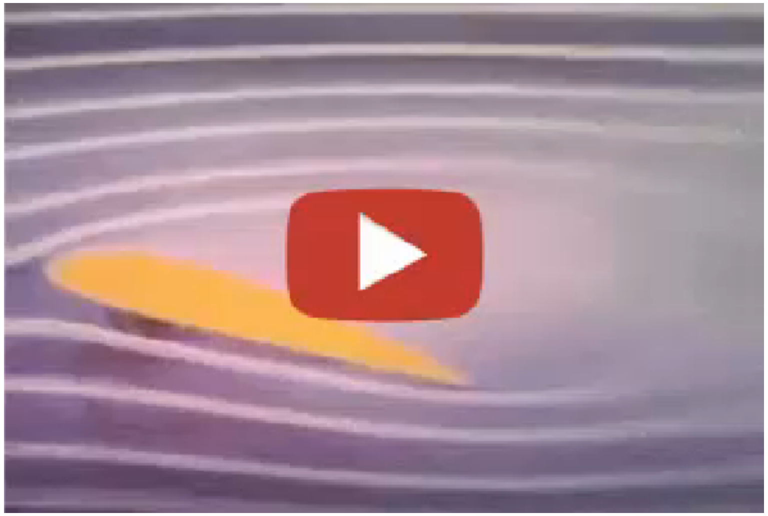
If this happens, the flow "unsticks" from the surface, or "***separates***".

At what angle does this happen? It depends on the ***Reynolds Number***.
The Reynolds Number, "Re", is basically the ratio between the viscosity or "stickiness" of the air, and its kinetic energy. Therefore Re is determined primarily by two things:
The size of the object in question, and how fast it's going. Things that are small and going slowly – e.g. insects – experience very low Reynolds Numbers, like they're swimming in honey. They almost never experience flow separation, despite steep angles and tight surface curvatures. But things like sports balls, cars, and airplanes (which are bigger and bigger, and go faster and faster) experience larger and larger Reynolds Numbers,
i.e. they move through air that is less "sticky" and more prone to separation.

Angle of Attack, and the Stall







Angle of Attack, and the Stall

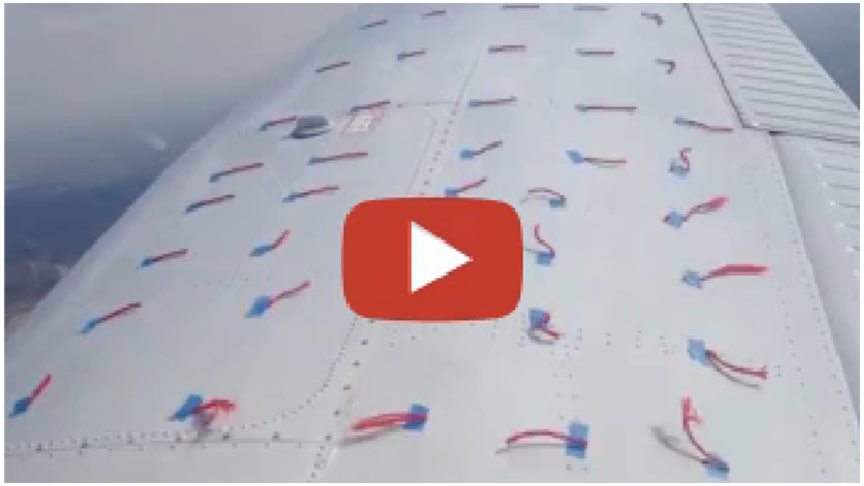
- ***Angle of attack*** (a.k.a. α) is the angle between the free-stream / far-field airflow and the wing's "chord line" (from front tip to trailing edge)
- If a wing's *critical angle of attack* is exceeded, the airflow separates, i.e. it can no longer "make the turn" to flown down the upper surface of the wing near the back.
- This is called a ***stall***. The wing basically "stops working".
- The wing typically does not stall all at once. On some airplanes, it does. But on nearly all airplanes, the stall starts at the trailing edge and, if alpha continues to increase, the flow "unstick" location moves gradually forwards. On most airplanes, the inboard region stalls before the wingtips. More about this soon.
- In any case, stalls are typically gradual, and can be sensed by the pilot (and the situation can be corrected) before the airplane is "falling out of the sky".

Stall Visualization with Tufts

BAD:
Wingtip stalls first

GOOD:
Wing root stalls first,
tip never stalls

Douglas DC-3, Boeing 737 with slats off

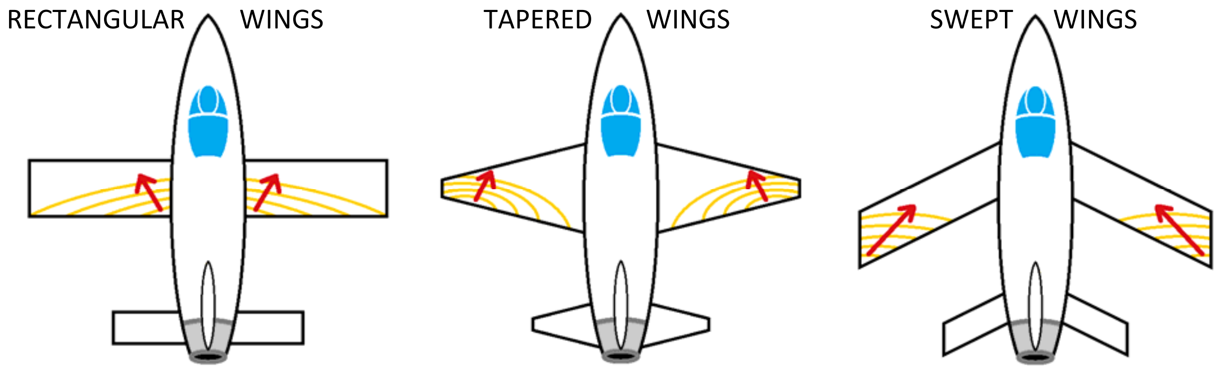


Piper PA-28, Zenith CH-601

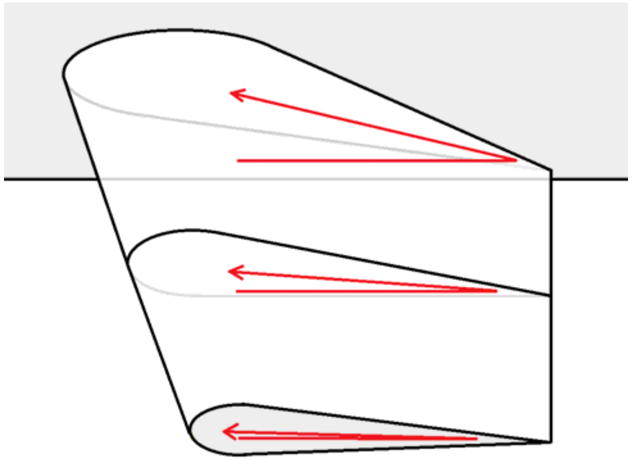
Stall Visualization with Tufts

- For many decades, the stall characteristics of new wing designs have been studied by stalling the airplane (or at least a wind-tunnel model of the wing) with tufts attached to the upper wing skin.
- This is still done for small airplanes
- Ideally, the wing (1) does not stall all at once, but rather gradually, and (2) stalls inboard before stalling outboard, so the ailerons continue to work during the progression of the stall.

Preventing Tip-Stall



Wing Twist a.k.a. WashOut:

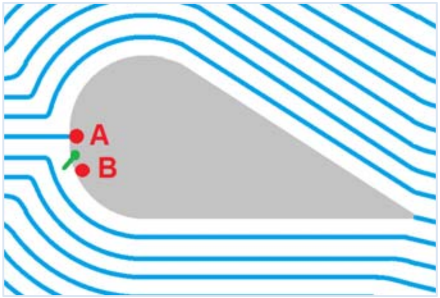


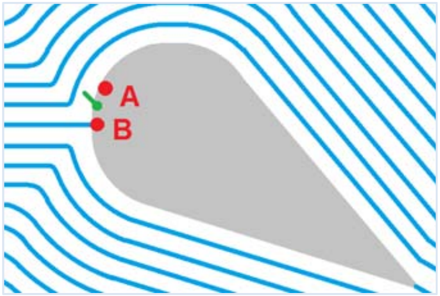
MiG-17

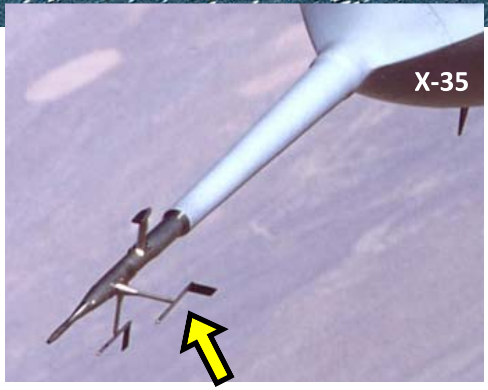
Preventing Tip-Stall

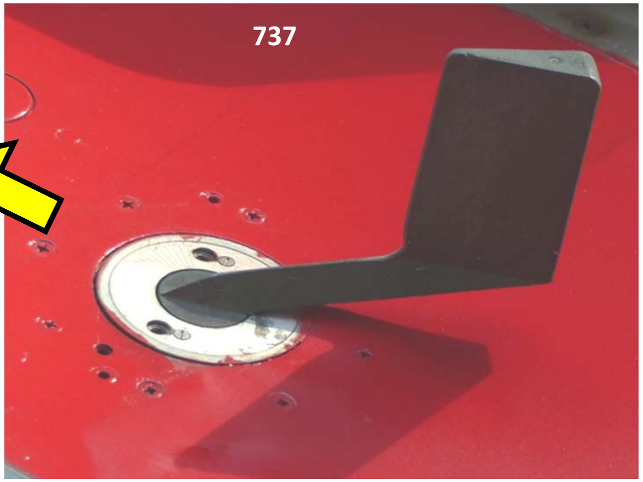
- On airplanes with ***rectangular*** (a.k.a. ***"Hershey bar") wings***, the inboard region naturally tends to stall first. That is one reason why many training airplanes still have rectangular wings, despite the higher induced drag. (Another reason: They are cheaper to manufacture).
- However, on airplanes with swept and/or tapered wings (i.e. on most airplanes), the ***wingtips naturally tend to stall first***. That's bad because (1) that's where the ailerons are, i.e. the pilot loses roll control, and (2) on swept wings, loss of lift at the wingtip causes the center of lift to move forwards, generating a nose-up moment, increasing α, worsening the stall.
- Therefore, most wings have ***twist/washout*** (wingtips at lower angle of incidence) to keep the wingtips from stalling. (This brings more of the lift inboard, which has the nice side-benefits of lowering induced drag and reducing structural weight).
- Some wings (e.g. Beech 18, Cirrus, Gulfstream IV, some modified Bonanzas and Globe Swifts…) have ***stall strips*** to force the inboard region to stall first.
- Some early swept-wing jets (MiG-17, Caravelle, Su-22…) had **wing fences**: chord-wise vertical strips on top of the wing, to block span-wise flow to keep the tips from stalling. (More about spanwise flow, coming soon).

Detecting the Stall







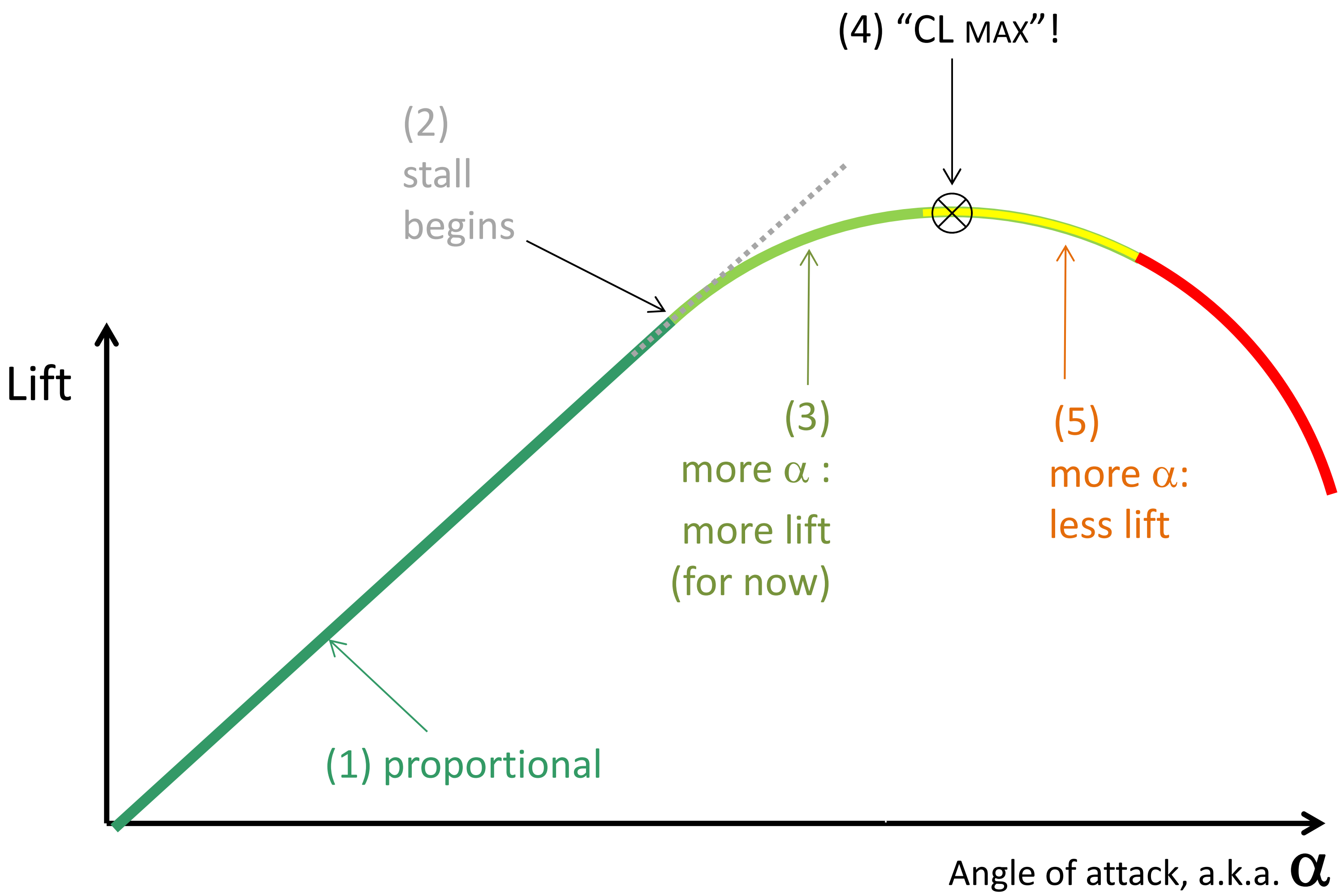


Detecting the Stall

- The ***stagnation point*** is where the air hits the wing, stops, and splits: Some of it goes up, some of it goes down.
- As alpha increases, the stagnation point moves downwards and aft.
- A ***stall vane*** is a switch-like sensor that is pushed down by the air when the stagnation point is ahead/above the switch, and then the switch is flicked up when the stagnation point moves below/behind it at some high angle of attack (i.e. when the air flows past the switch going upwards/forwards rather than going downwards/backwards). This usually triggers an aural warning horn in the cockpit.
- In the diagram on the previous slide: At some low-ish angle of attack, stagnation happens at point "A" on the leading edge. (Notice how air moves ***downwards*** past the "switch" between A and B). At some high-ish alpha, the stagnation point is now at "B". (At that high-ish alpha, air will move ***upwards*** past the "switch" between A and B).
- Most jets, and some small airplanes, have a weathervane-like ***angle-of-attack sensor*** that can provide continuous information about the angle of attack, not just whether it's higher or lower than some critical angle. The indicator is typically a series of colored lights, or a needle that moves within colored ranges. The angle at which the wing begins to stall, and/or the "CL max" angle, can be marked on the display.
- Sometimes, a "Lift Reserve Indicator" is used instead, providing generally similar information, but from a sensor that picks up static pressure over an angled surface.

(see next slide)

What angle of attack maximizes lift?



As the angle of attack increases…

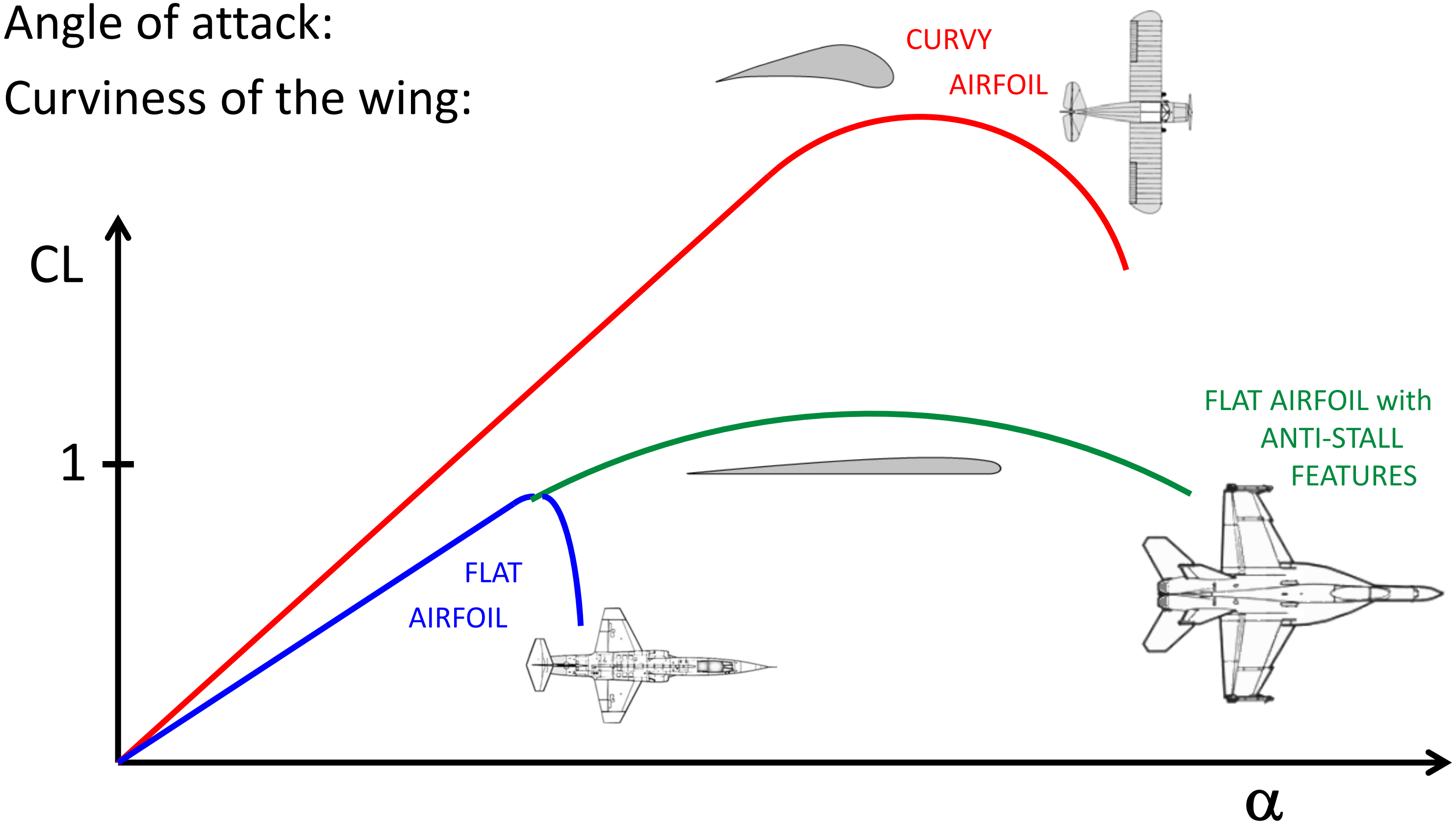
- (1) During normal flight, lift is linearly proportional to angle of attack. Double the angle of attack, and you double the lift. (Reduce the speed by √[½] and you have to double the angle of attack if you want to get the same amount of lift).
- (2) At some angle of attack, part of the wing begins to stall. So the relationship is no longer quite linear.
- (3) As the angle of attack increases, the added lift from the non-stalled region is ***still*** greater than the loss of lift from the growing stalled region…
- (4)… until "CL max", the top of the curve. That's the angle of attack where any increase in alpha will cause an increase in lift at non-stalled areas that will be ***canceled out*** by the growth of the stalled area.
- (5) Past "CL max", any increase in angle of attack will cause much more wing area to stall, overwhelming any increase in lift at non- stalled regions.

Notice how the max lift is not "before you stall". It's when part of the wing is already stalled!

- Notice how the colors and the "max" correspond to the angle of attack indicator on slide 67.
- On most airplanes, you want to stay on the green parts. But if you're landing a bushplane (or a C-17!) in the wilderness and you need to be able to stop in the shortest distance possible, then you need to land as slowly as possible, so you try to aim for the angle of attack that puts you at the top of the curve. But landing just a few mph below the max (i.e. in the "downhill" part of the curve) can be dangerous, as any decrease in headwind (or a gust from behind) can cause the airplane to fall quickly.

How much lift can a wing generate? Depends on…

- Size of the wing
- Speed
- Angle of attack:
- Curviness of the wing:



How much lift can a wing generate? That depends on…

- (1) The **size** of the wing. This is an intuitive linear relationship:
If you take a wing and make it twice as big (i.e. if you double the wing area), it can make twice as much lift!
- (2) **Speed** (and **air density**), which depends on the dynamic pressure, $\frac{1}{2} \rho v^2$.
Double the speed while keeping everything else the same, and the wing makes four times as much lift.
Fly through air that is half as dense (e.g. fly at a little over 20,000 feet) and the wings make half as much lift.
- (3) **Angle of attack**. As long as the airplane is not entering a stall, lift is proportional to angle of attack.
If the angle of attack doubles, the wing makes twice as much lift.
- (4) The **curviness** of the wing. Wings that are flat do not force the air to curve downwards as much,
so they do not generate are much lift (per square foot, at a given speed.

There are two ways in which a wing can be "curvy":

- It can be thick, i.e. have a high distance between lower wing skin and upper wing skin. And/Or…
- It can have "camber", or asymmetry. Zero-camber airfoils have the same curvature on the bottom as on the top. Airfoils with flat bottoms have some camber. Airfoils with a lot of camber have concave bottoms.

Remember that the lift force is almost always equal to the airplane weight. So when one of these factors goes up, another must go down.

Most of the time, (1) and (4) stay constant, while (2) and (3) vary antagonistically. If the speed goes down by half (at a given altitude) then the angle of attack must go up by four times, in order for the wing lift force to continue to match the airplane's weight. If the airplane climbs to a little over 20,000 feet (where the density is about half of sea level), increasing the speed by 1.4 (the square root of 2) will allow for the same angle of attack to be used, while the wing lift force continues to match the airplane's weight.

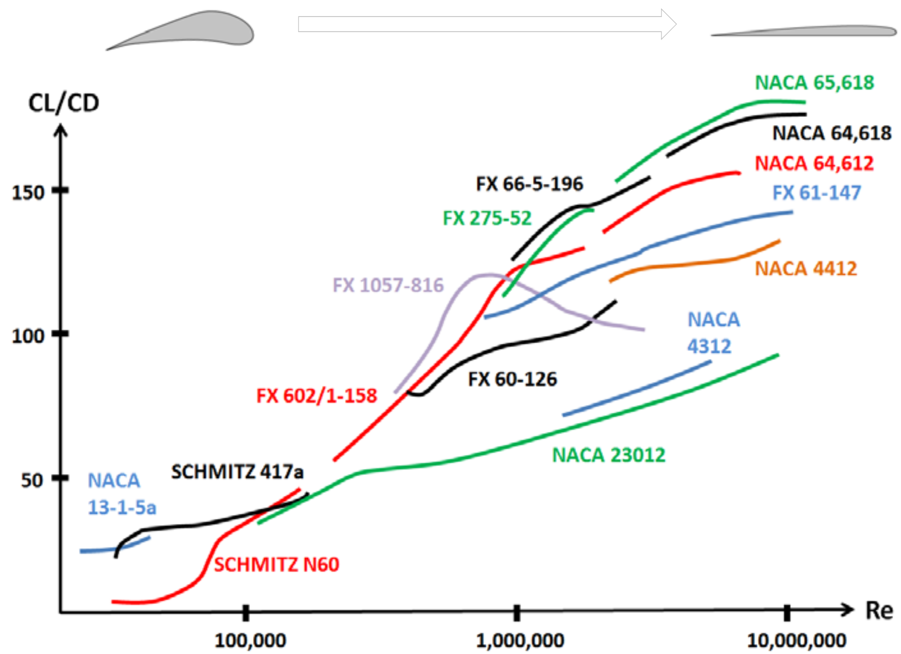
As we will see (starting on slide 74), during takeoff and landing, it is possible to change (1) and (4) using flaps and slats.

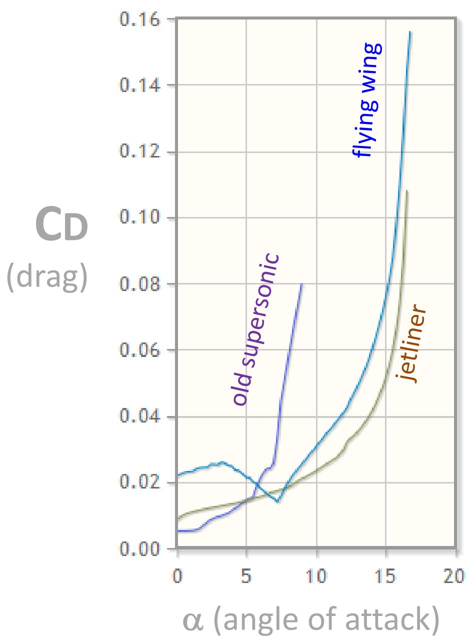
Some fighters have "maneuvering flaps" that deploy to make the wing curvier whenever high angles of attack are sensed.

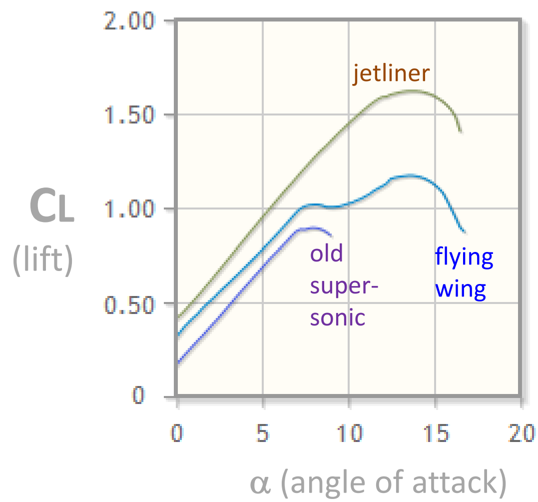
Different airfoils (i.e. different wing cross-sections) have different "**Coefficient of Lift (CL) curves**". The CL is how much lift an airfoil generates, per square foot, per unit of dynamic pressure (e.g. per speed, at sea level). So the CL of an airfoil is a number that factors out the wing size and dynamic pressure, and tells you how good a certain wing shape is at generating lift, only as a function of angle of attack.

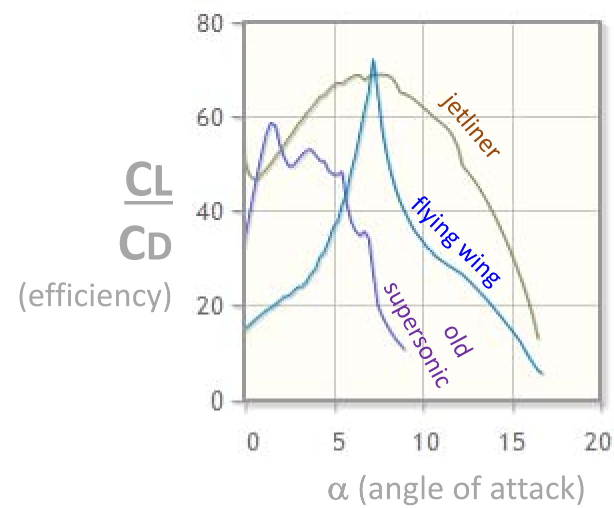
In order to land on a runway of a certain length, an airplane must be able to fly at a certain slow speed, without the angle of attack getting too close to the stall. This requirement – to safely make enough lift at the desired landing speed in order to be able to use runways of a certain length – determines the wing size of a new airplane model. What determines the airfoil (cross-section)? Well…

Which airfoil to choose for a wing?





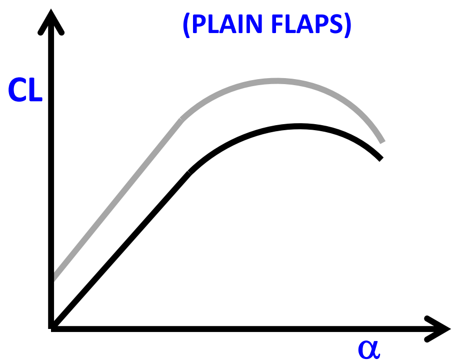




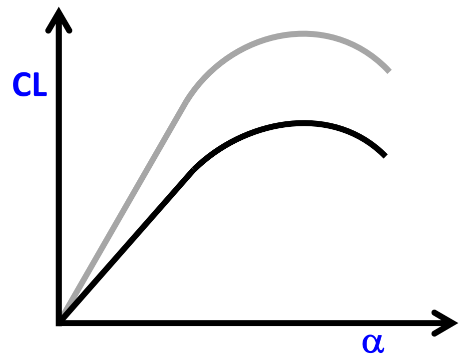
- There are whole books out there full of airfoils and their CD (coefficient of drag) and CL curves. They were invented by different researchers and engineers due to various properties, such as their lift and drag (and pitch moments, etc.) at various speeds and sizes and angles of attack. There are airfoils optimized for bushplanes, fighters, airliners, gliders, stealth airplanes, ultralights, model airplanes / UAVs, and everything in between.
- Certain design choices, e.g. trans-sonic cruise or a tail-less configuration or very high aspect ratio wings, strongly favor certain families of airfoils over others. This makes it easier for the designer to start choosing an airfoil.
- Do we just want the airfoil with the highest CL? No! For each airfoil we are considering, which one has the ***highest lift-to-drag ratio*** at the Reynolds number (combination of speed and size) where we want to cruise?
- However: An airfoil highly optimized for some cruise speed may perform poorly at slow speeds (e.g. stall abruptly or at low-ish alphas). So in practice, a "compromise" airfoil is chosen that is still very good at cruise (high CL/CD, but not ***the*** highest) but also pretty good at slower speeds (high CLmax, but not ***the*** highest).
- It's all priorities and compromises. A bushplane designer may choose an airfoil that is optimized for slow speeds and high angles of attack, so that the airplane can take off and land in the minimum amount of room possible (highest CLmax possible), even if this landing-optimized airfoil lowers the speed and efficiency during [faster] cruise flight.
- For example, the previous slide has the CL (lift), CD (drag), and CL/CD (lift-to-drag ratio i.e. aerodynamic efficiency) of three airfoils: a modern jetliner (Whitcomb), a flying wing (Roncz Markse7), and an old supersonic airplane (NACA 63206). The supersonic one is very efficient but only at low alphas, i.e. while flying very fast and almost "slicing the air like a knife". Also, it stalls at a very low alpha. The flying wing has its advantages (more details in slide 229), but it only has low drag at a very narrow range of alphas, i.e. it has to be flown "exactly right". The airliner wing has good aerodynamic efficiency at a wide range of alphas, and also makes a lot of lift before it stalls (and this is without flaps or slats!). Due to its camber, it makes quite a bit of lift at zero angle of attack. However, note that this graph is just for one speed. As the upper-right graph shows, different airfoils "win" (have the highest CL/CD) at different speeds.
- In general: Airplanes flown at lower Reynolds numbers (i.e. at slow speeds, especially if the wing chord is small, e.g. bushplanes and UAVs) tend to have curvier airfoils, with more camber (asymmetry) and greater thickness. Airplanes flown at higher Reynolds numbers (i.e. fast, especially if large) have thin airfoils with less curvature. Part of the reason is that, while going fast (i.e. being exposed to more air per second), air does not need to be deflected downwards very steeply in order for enough lift to be generated. Another part of the reason is that, at higher Reynolds numbers, flow separates (stalls) at lower surface angles, so wings cannot curve as much: steeper regions will locally stall. Alternately, at slower speeds, it is curvier airfoils that can be flown at higher angles of attack before they stall.
- As we will see, using "high-lift devices" (i.e. changing the shape of an airfoil in flight) allows for better cruise efficiency AND slower flight during takeoff/landing than any single airfoil shape could. So a fast airplane may have a "flat" airfoil with very high CL/CD for cruise, and then rely on high-lift devices to make the airfoil "curvier" at slow speeds to make more lift and prevent stalls.
- Many tools make airfoil comparison easy. For example, see http://airfoiltools.com/compare . A list of websites and software that give you CL and CD for various airfoils, depending on alpha and Re, can be found at http://forums.x-plane.org/?showtopic=54036 . There are lots of great resources out there about airfoil selection, e.g http://itlims.meil.pw.edu.pl/zsis/pomoce/BIPOL/BIPOL_1_handout_8A.pdf and http://issuu.com/billhusa/docs/airfoil_selection . What airfoils are used by actual airplanes? See http://www.aerofiles.com/airfoils.html and http://m-selig.ae.illinois.edu/ads/aircraft.html .

High Lift Devices Enable Slow Flight

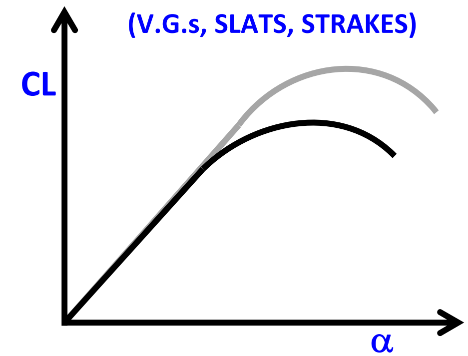
INCREASED CAMBER
(PLAIN FLAPS)



INCREASED CHORD
(FOWLER FLAPS)



BOUNDARY LAYER CONTROL
(V.G.s, SLATS, STRAKES)



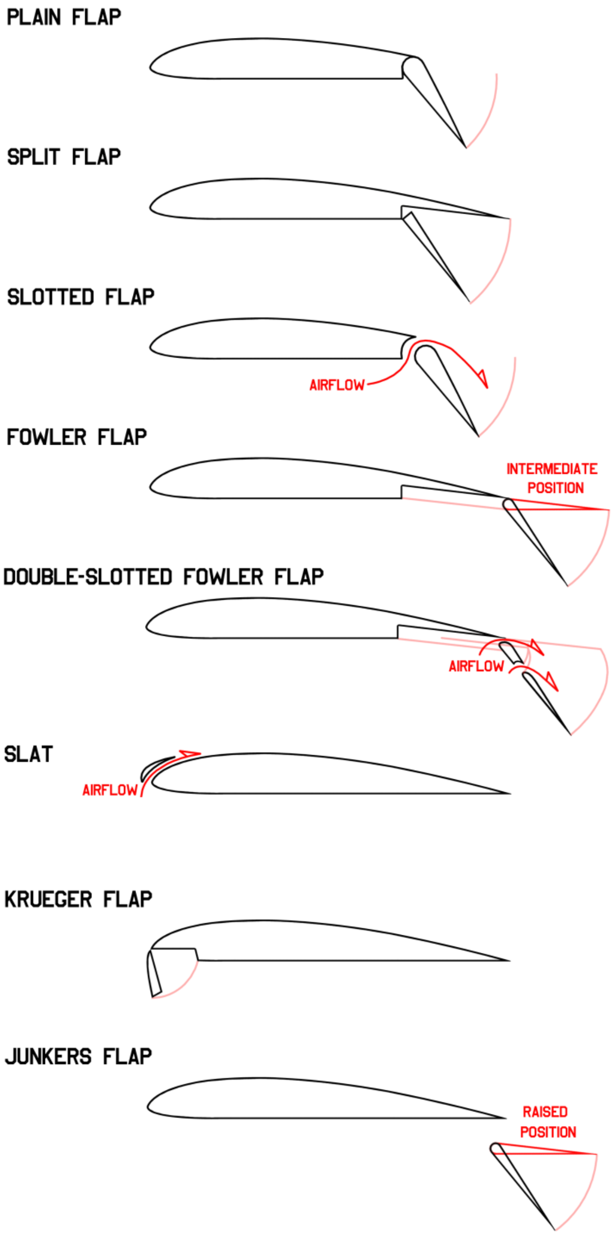
High Lift Devices Enable Slow Flight

High Lift Devices increase the CL of the wing, allowing the airplane to fly at higher angles of attack without stalling. This allows the airplane to fly more slowly, so it can take off and land using shorter runways.

This is accomplished in three ways:

- (1) **Increase the camber (i.e. the curviness) of the wing** by bending the trailing edge (and sometimes also the leading edge) downwards.
- (2) **Increase the chord (and therefore the area) of the wing** by extending the trailing edge backwards (and sometimes the leading edge forwards). Bigger wing, more lift!
- (3) **Energize the Boundary Layer** (the air that is right over the skin) by stirring it up (Vortex Generators, LERXs, vortilons, strakes) or by bleeding some air through the wing (slots). Make the Boundary Layer air “stickier” so the wing can fly at higher alpha without stalling.
  (More on Boundary Layers and “stickiness” when we discuss Viscous Drag)

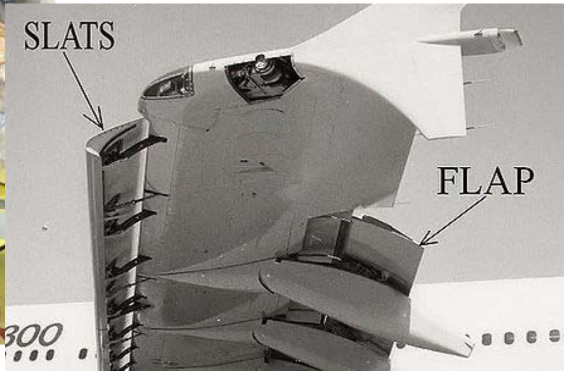
High-Lift Devices



F/A-18C

747

A300



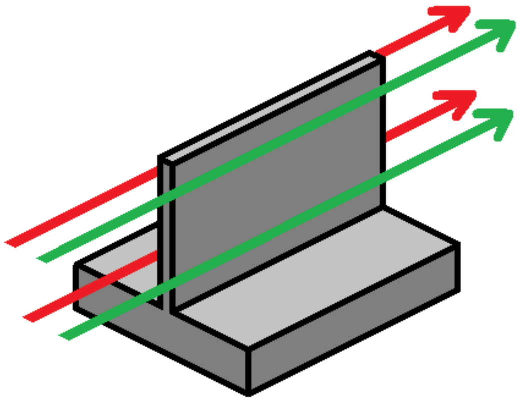
In practice, it's more complicated:

- Most flaps increase camber AND chord (i.e. extend downwards AND backwards), AND have slots! Most airplanes have slotted flaps. You can see light through them!
- Slats on the leading edge typically extend forwards and downwards, AND open up slots. However, many fighters have non-slotted slats, a.k.a. "leading-edge flaps".
- Generally, "flaps" are on the trailing edge and "slats" are on the leading edge, but Krueger flaps are on the leading edge. They increase camber and chord, too.
- Some airplanes have flaperons and/or drooping ailerons. These are trailing-edge surfaces that actuate differentially for roll control, but can be deflected downwards together for slow-speed flight.
- Some airplanes have slots that are always open (e.g. Swift), some only open at high angles of attack (e.g. Me-262).
- Yes, it's counter-intuitive, but it's true: Bleeding a little bit of air through a slot from the bottom of the wing out the top of the wing allows the wing (or the flap) to fly at a higher alpha without stalling! The "mission" of the wing is to deflect air downwards… but, by allowing a little bit of air to flow upwards through the slot to "energize" the airflow over the top of the wing (or flap), the air over (and under!) the wing (or flap) ends up being deflected downwards ***more***, overall.
- Note: Flaps and slats, when deployed at small angles, can substantially increase lift (especially at slow speeds) without adding much drag. However, large-angle deflections will add substantial drag without much of an increase in lift. Therefore, flap and slat deployment angles during takeoff and climb-out tend to be small, and more aggressive (draggier) steeper angles are used during landing.

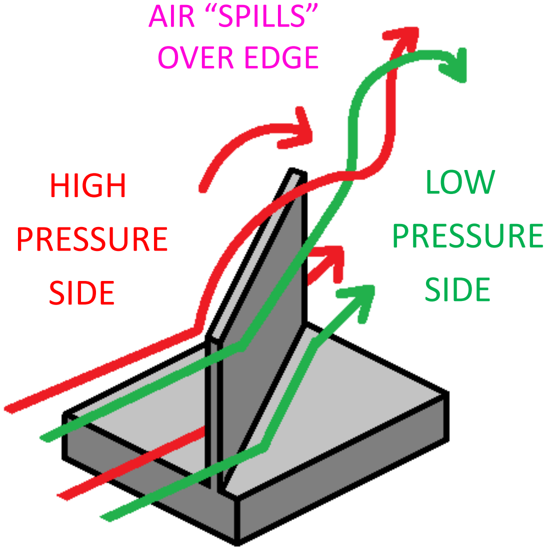
NASA and the Air Force Research Labs have been testing "FlexSys"/"FlexFoil" flaps that actually bend down a flexible "Adaptive Compliant Trailing Edge", more like an animal skin, rather than moving a plate with an edge or a gap. This technology may soon allow for high-lift devices that are less draggy.

A Key Concept: Vortices

EDGE-ON AIRFLOW:
(ZERO ANGLE OF ATTACK)



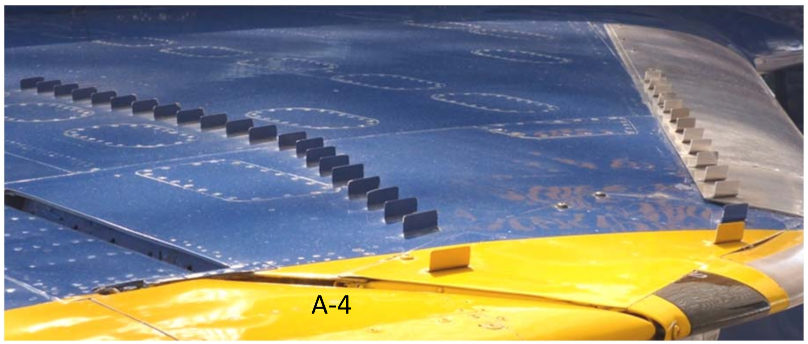
FLOW HITTING
PLATE AT ANGLE:



A Key Concept: Vortices

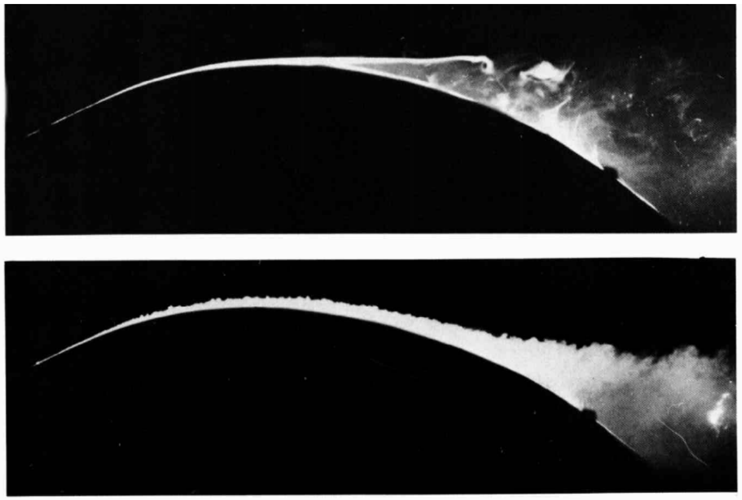
- A fluid flowing past a thin plate oriented parallel to the flow (i.e. the plate "slices the air like a knife", at zero angle of attack) will not experience changes in its path. It will just slow down a little due to viscous forces. (More about this when we talk about viscous drag).
- A fluid flowing past a plate at an angle to the flow will experience high pressure on the side of the plate being hit by the flow, and low pressure on the side of the plate that is away from the flow (e.g. the bottom and top of a wing, respectively). Some of the high-pressure fluid from the front side will spill over the edge, being "sucked into" the low-pressure back side. This forms a vortex, a tornado of spinning fluid, originating at – and centered on – the edge of the plate. (More about this when we talk about induced drag).

Vortex Generators

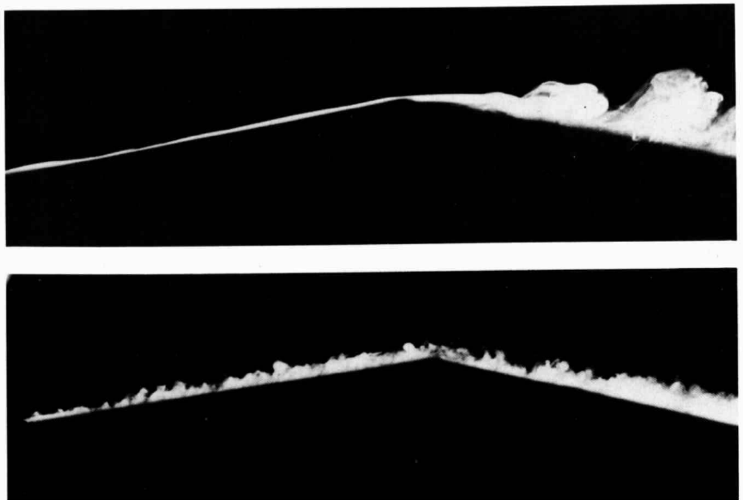


- **Vortex generators** are small flat plates on top of some wings (and also sometimes on tail fins) set at a slight angle to the airflow. They allow for flight at higher angles of attack without stalling, which lowers the takeoff and landing speeds and thus the required runway length. They also allow for more Gs to be pulled in flight without stalling.
- They generate tiny vortices that flow just over the surface of the wing (or tail fin). ***Turbulent air is more "sticky"*** (see right), so wings with vortex generators can be flown at higher angles of attack before they stall. Also, flaps (and control surfaces) aft of vortex generators can be deflected more steeply without stalling (i.e. while preserving the ability of the air to follow the surface that is deflecting away from the airflow) than if the VGs were not there.
- VGs always add drag, so while they reduce the airplane's minimum speed, they also reduce the cruise speed and the top speed, and thus the fuel efficiency.

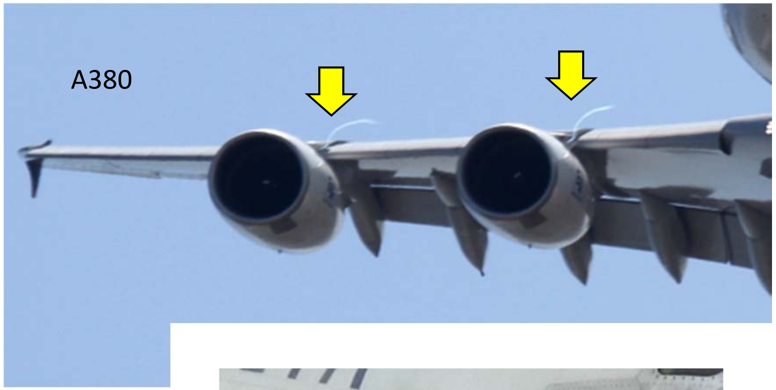
Note: Airliners almost never have VGs on their first flights; VGs on airliners are a sign that some aerodynamic surface did not perform in tests as well as expected, and needed a "band-aid" in order to delay its stall to higher angles. (Whenever you see a VG on an airliner, you can bet that somewhere there is an aerodynamicist sadly shaking his/her head in disappointment).



156. Comparison of laminar and turbulent boundary layers. The laminar boundary layer in the upper photograph separates from the crest of a convex surface (cf. figure 38), whereas the turbulent layer in the second photograph remains attached; similar behavior is shown below for a sharp corner. (Cf. figures 55-58 for a sphere.) Titanium tetrachloride is painted on the forepart of the model in a wind tunnel. *Head 1982*



“Chines” (Vortex-Generating Strakes)



Chines, Vortex-Generating Strakes, Vortilons, and LERXs

- **Chines (VG strakes)** are fins mounted just ahead of the wing. Examples include the "shark fins" mounted on airliner engine nacelles, and the strakes that stick out of the sides of the fuselage by the wing leading edges of some Cirrus airplanes and RV-8s, and near the nose of MD-80s. During cruise, they do almost nothing, simply slicing the air like a knife (i.e. zero angle of attack or sideslip). But at slow speeds, when the angle of attack is high, air flowing past the strake will hit it at an angle, making a vortex that flows over the top of the wing and along its upper surface, allowing the wing (and, typically, its flap) to fly at higher alphas without stalling.


F/A-18

- **LERX**, or Leading Edge Root eXtensions (a.k.a. LEXs), are found in most modern fighters, most prominently on F/A-18s. The leading edge of the wing extends forwards near where it meets the fuselage, creating two long, low-aspect-ratio extensions just behind and to either side of the pilot. These work just like chines/ VG strakes.
- **Vortilons** are vertical surfaces, found around (or just under) the leading edges of some airplanes (e.g. 727, 737, ERJ-145, Sabreliner, EZ, Harrier, Challenger 300). Like LERXs and VG strakes, during cruise they are at zero angle of attack and do not noticeably impact the airflow. But when alpha increases, the span-wise component of the flow increases, i.e. flow along the bottom of the wing angles outwards towards the wingtip and flow over the top of the wing angles inwards towards the fuselage. (This is the same phenomenon as the wingtip vortex). So at slow speeds, the air over the wing curves inboard, and the air under the wing curves outboard, hitting the vortilons from the side, causing them to make vortices… which, again, flow over the upper surface of the wing and allow for flight at higher angles of attack before the wing stalls.


HARRIER

- All of these features allow for flight at higher angles of attack without stalling, which lowers the takeoff and landing speeds and thus the required runway length. They also allow for more Gs to be pulled in flight without stalling. Note that "regular" VGs (little ones on top of the wing) always add drag, while the features on this slide only add drag during high-alpha flight. (The exception is some VGs on top of the leading edges of retractable flaps, which are not exposed until flaps are deployed, and thus also only add drag just before landing, e.g. on the 767).


CHALLENGER 300

Drooped Wingtips


MUSKETEER

CESSNA 182

DHC -2


CESSNA 182

Drooped Wingtips

Most "wingtip devices" – such as winglets and raked wingtips – exist to reduce induced drag. (More about this when we cover induced drag).

One exception are drooping wingtips. These are used to increase lift.

Flight at higher angles of attack generate more spanwise flow.
In other words, the more the airplane slows down,
the more air under the wing is flowing slightly outwards, towards (and past) the wingtip.

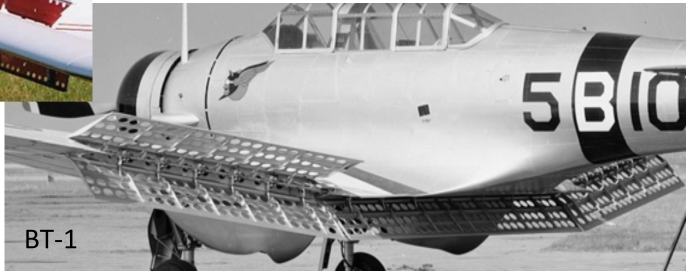
Drooping the wingtip causes this air under the wing, which flows towards and past the wingtip during slow flight, to be deflected downwards. This generates more lift.

In other words, drooping wingtips are like flaps for the wingtips.

They are most often seen (typically along with vortex generators) in single-engine airplanes that have been especially modified to fly extra slowly, e.g. for towing banners, towing gliders, and/or for use in remote areas away from airports (i.e. as bushplanes).

Note: Drooped tips change the lift distribution of the wings, making more lift out close to the tip. This (1) increases the intensity of the wingtip vortex and induced drag, and (2) increases the structural bending moment at the wing root. For this second reason, modifying an airplane by adding drooped tips often reduces the maximum weight that the airplane is certified to fly at.

Spoilers & Air Brakes



Spoilers

- Some airplanes do have **air brakes**.
- However, on nearly all airlines,
the plates that stick up from the top of the wing are ***spoilers***, which work slightly differently.
- **Spoilers “dump” lift by deflecting some air upwards**
(i.e. causing wings to work less well, decreasing CL).
- During flight, deploying spoilers forces the alpha to increase.
This increases the drag of the wings and the fuselage.
So **the whole airplane acts as an air brake**!
- Upon landing, deploying spoilers means the wings “dump” their lift and **the wheels have to support the airplane’s weight: Better traction, better braking**. Airplane comes to a stop using less runway.
- On some airplanes, **spoilers are used for maneuvering**, as well as ailerons. This was introduced on the B-47 because the ailerons on the trailing edge were twisting the thin wings, causing aileron roll reversal.

Drag

Four causes:

- Skin friction, a.k.a. viscous drag
- Flow separation, a.k.a. pressure drag
- Drag due to lift, a.k.a. induced drag
- Wave drag, a.k.a. compressibility drag

Drag

Drag is caused by four separate phenomena:

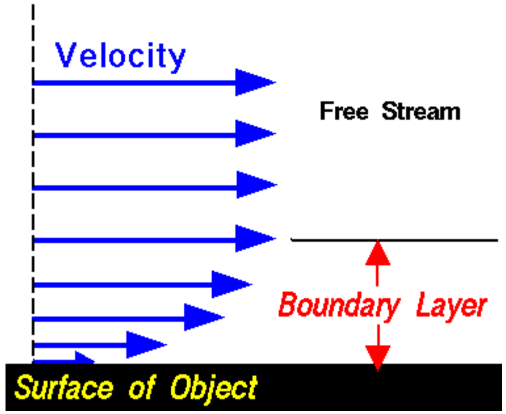
- ***Viscous drag***, a.k.a. skin friction
- ***Pressure drag***, especially strong if there is flow separation
- ***Induced drag***, a.k.a. drag due to lift, related to wingtip vortices
- ***Wave drag***, a.k.a. compressibility drag, due to shockwaves that start to form when the airplane approaches the speed of sound

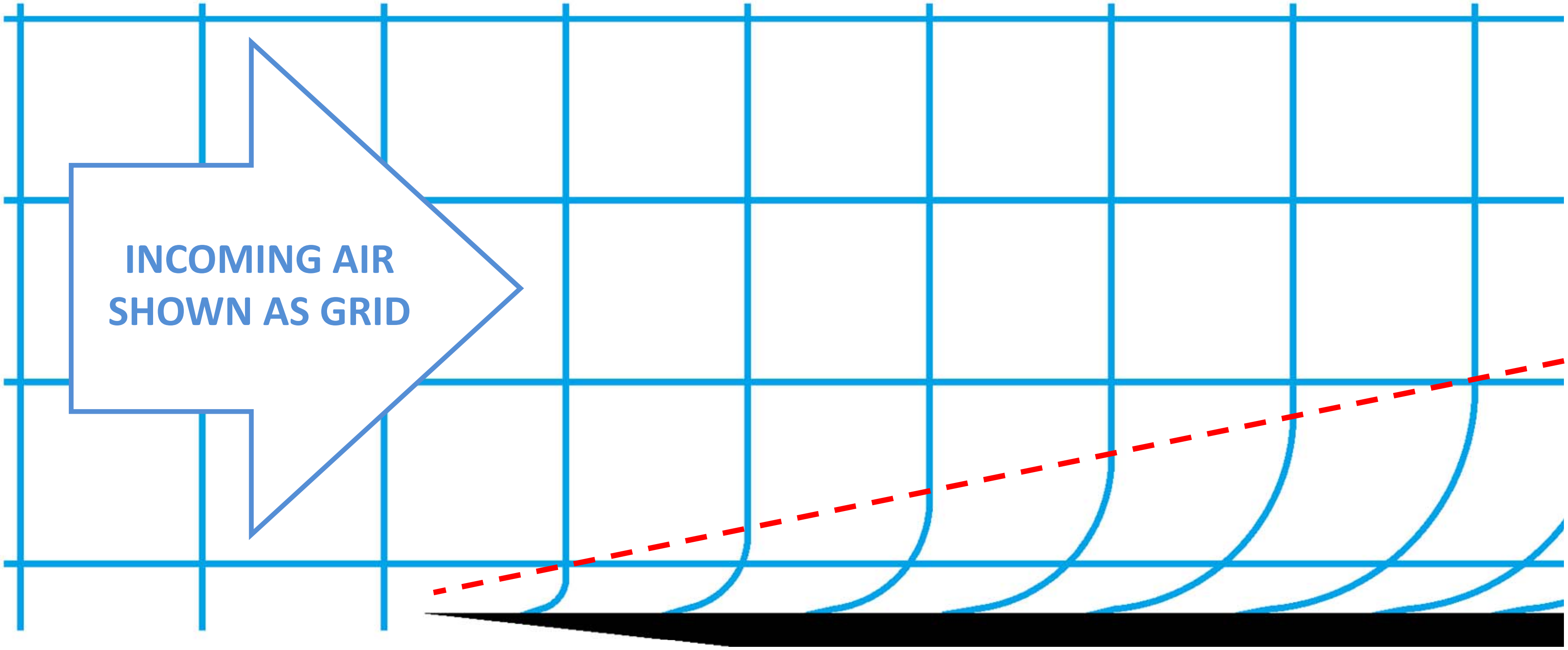
Note about the F-22 photo in the previous slide, as well as the vortex photos in slides 82, 83, 120, and 258:
Here are two key principles to remember.
(1) When you compress a gas, you make it hotter. When you lower the pressure of a gas, you make it colder. And…
(2) Hot fluids are able to “hold” more stuff dissolved in them than cold fluids. Heat up some water to near boiling, and you’ll be able to dissolve (i.e. “disappear”) more salt or sugar into it than you would into cold water. And if that water (which you heated up and dissolved salt or sugar into) cools down later, you’ll see solid crystals forming in it, because the cold water can’t “hold” all the salt/sugar anymore.

Unless you’re in the middle of the desert, air generally has some water dissolved in it (which we call “humidity”). As some air gets colder (e.g. overnight), it experiences a rise in its relative humidity (i.e. how much water it’s holding, as a percentage of how much water it COULD hold at that temperature). It if cools down enough, and if it was humid enough to begin with, the relative humidity will hit 100% and some of the water will precipitate out of the air as fog or dew (as typically happens in the early morning). We say the air cooled past its “dew point”.

Airplanes lower the pressure of the air around them, especially in some regions such as over the wings (to generating lift), along the centerline of a vortex (due to “centrifugal” effects as the air spins around), and in a cone-shaped region behind any “bumps” as the airplane approaches the speed of sound (when air moves away from the airplane in shockwaves, then turns back towards the airplane in what is called an “expansion fan”). So if the air is close to its dew point (e.g. it’s raining or some fog/clouds are nearby or just burned off), then around an airplane, water will condense out of the air and into a spray of liquid droplets in those airflow regions, making the pressure drop visible.

Viscous Drag

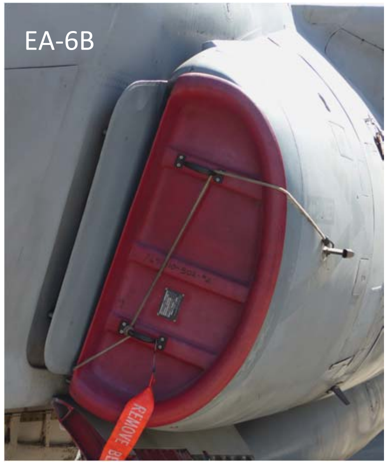


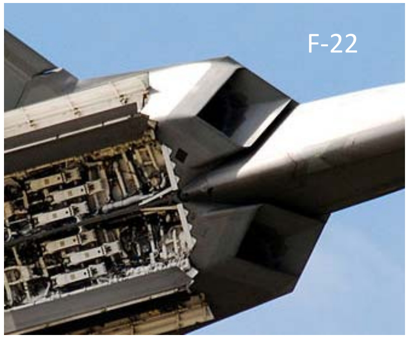


Viscous Drag

- Every surface on the airplane pulls the air along with it. Viscosity is the "**stickiness**" of the air. (Honey is very viscous).
- The airflow has a ***boundary layer*** of slower air over the skin.
- Each layer of air close to the airplane skin slows down the next layer of air, which then slows down the next layer of air, which then slows down the next layer… So the boundary layer (the region of air around the airplane that is moving at, say, less than 95% of the free-stream far-field airflow)
  gets thicker towards the back of the airplane: typically a couple feet thick by the tail cone of an airliner. (Notice how airliner skins are fastened in place by flush rivets everywhere except on the tail cone, the only place where you see button-head rivets instead. The tail cone is surrounded by a thick layer of slow-moving air, of air that has been "dragged along" by the airplane and moves almost together with the airplane skin).

Splitter Plates & Diverters



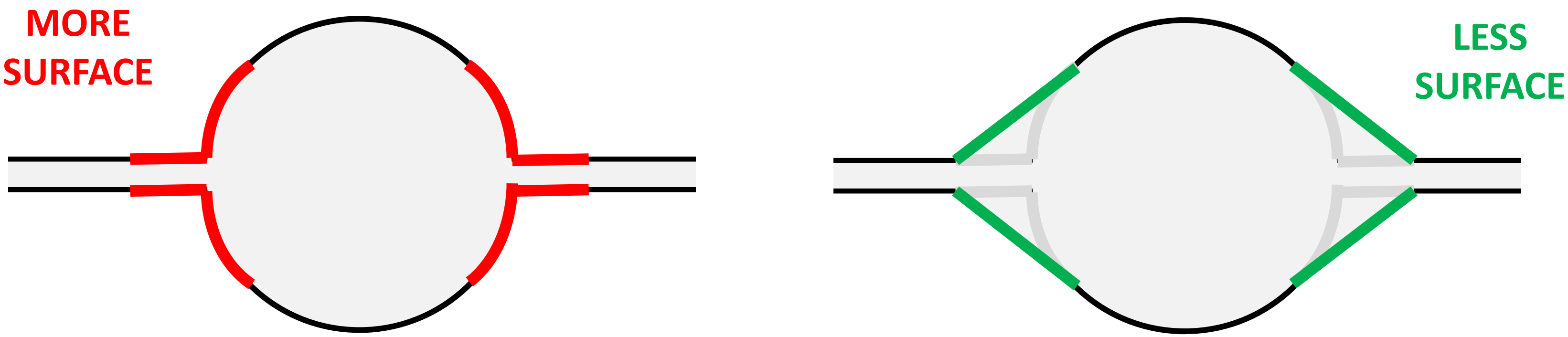


Splitter Plates

- Most jet fighters, which have engine air intake scoops on the fuselage, have a ***splitter plate*** or ***diverter*** between the side/bottom of the fuselage and the scoop opening. At the very least, they have a gap between the jet intake and the fuselage skin, rather than a flush inlet.
- This keeps the boundary layer from entering the engine. This is so that the engine only ingests fast, energetic air.
- The F-35 has a "bump" instead, to accelerate the boundary layer air. Some Chinese fighters also use this, e.g. the J-20 and new versions of the JF-17. This is a *diverterless inlet*.

Reducing Viscous Drag

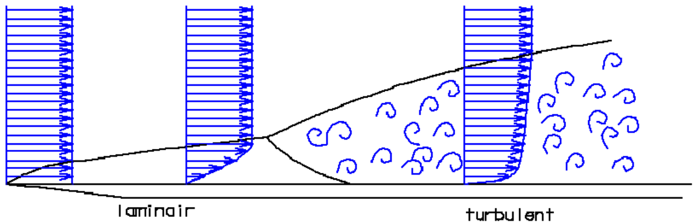
USE FILLETS AND BLENDED SURFACES TO REDUCE SURFACE AREA

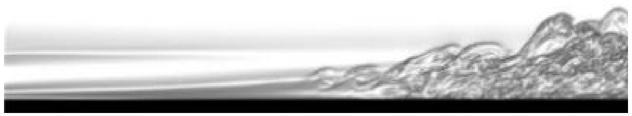


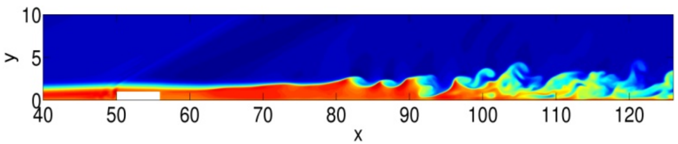
Ways to Reduce Viscous Drag

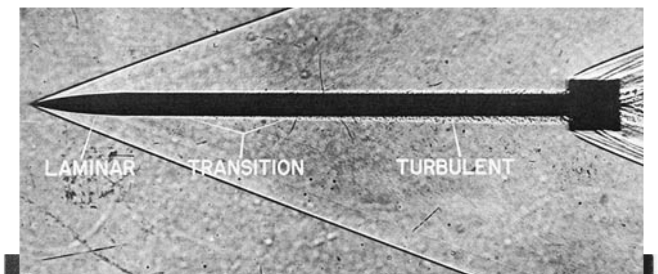
- Fly through **air that is less dense** and thus less viscous.
- **Lower the surface area**, i.e. use blended surfaces in corners. Sharp angles and grooves and corners usually contain "extra" surface area that could be removed if they are "filled in".
- Fly **more slowly**.
- Make the airplane **smaller** ;)
- Preserve Laminar Flow (next slide)

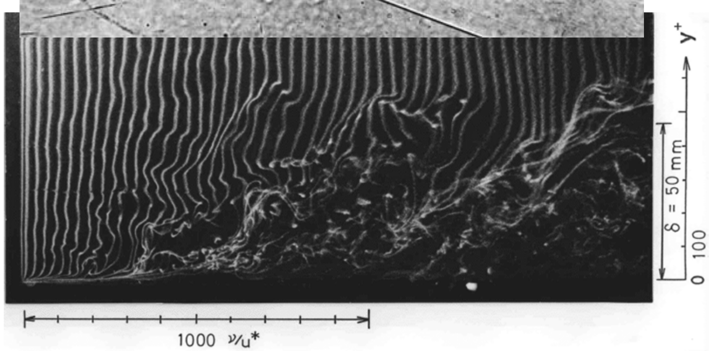
Laminar vs. Turbulent Boundary Layers









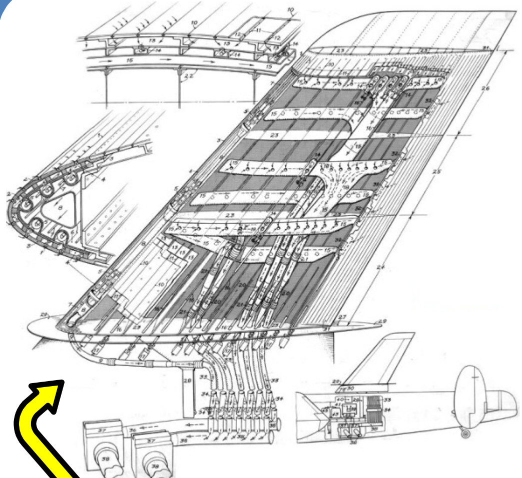


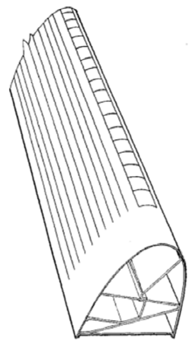
EXTRA SMOOTH SURFACES KEEP BOUNDARY LAYER LAMINAR RATHER THAN TURBULENT. LESS "STICKY".

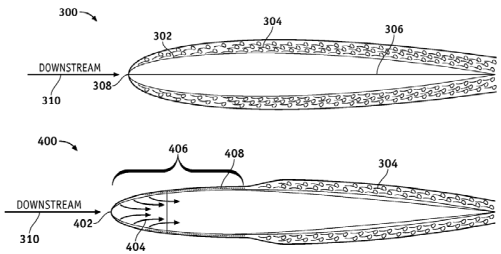
Ways to Reduce Viscous Drag

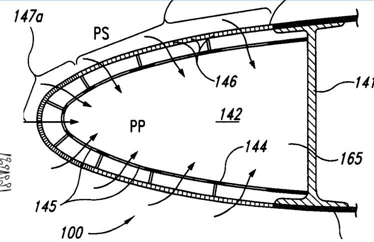
- **Preserve laminar flow**: "Laminar" flow consists of smooth parallel layers of air; "turbulent" flow consists of rough air tumbling over itself.
- Turbulent flow is "stickier", i.e. makes more viscous drag.
- Normally, the flow spontaneously "trips" from laminar to turbulent some distance from the leading edge.
- To reduce viscous drag, keep surfaces extra smooth to keep the boundary layer from "tripping" for longer. Use certain airfoil cross-sections with lower curvature that are better at keeping the flow laminar for longer.
- The picture on the right is a propeller blade flown during August of 2017, when most of the Pacific Northwest was immersed in wildfire smoke, i.e. sticky soot particles. Notice how the forward ~40% of the blade is clean, since it's being exposed to the same layer of air, which lost its soot when it hit the leading edge… but the aft ~60% is dirty, because turbulent flow means churning air, so the back of the blade is being exposed to "fresh" air that still has its soot particles. (Note: For similar reasons, turbulent flow is also more effective at cooling!) Notice also how imperfections (e.g. bugs and dings) trip the flow, i.e. have a wake of turbulent sooty air behind them. This is why you don't want too many bugs stuck to the leading edge of your wing: Each one causes a growing region of wing surface behind it to experience higher viscous drag due to the turbulent air there!

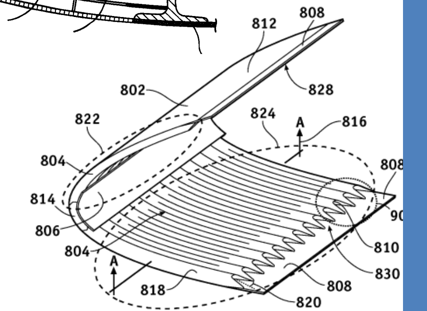
Laminar Flow Control







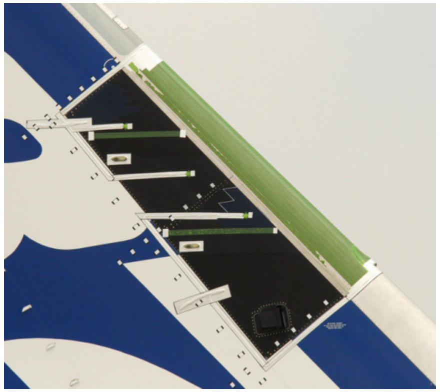


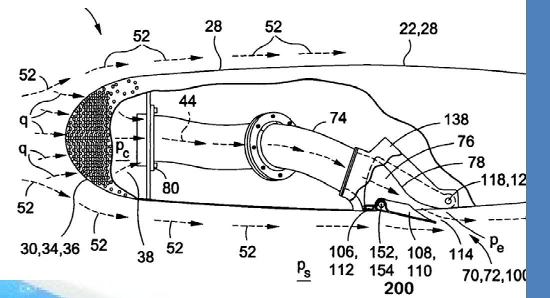


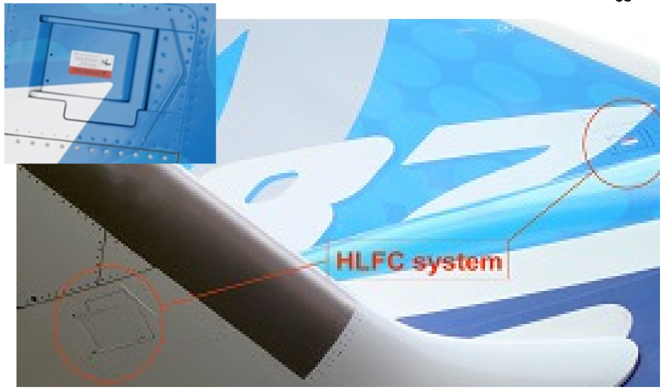

LANCASTER

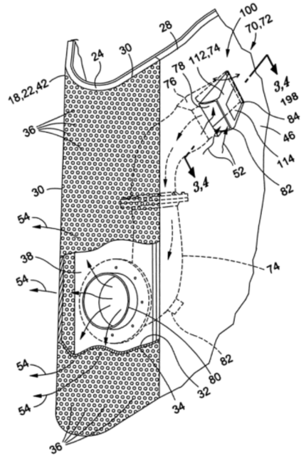

X-21


F-16XL









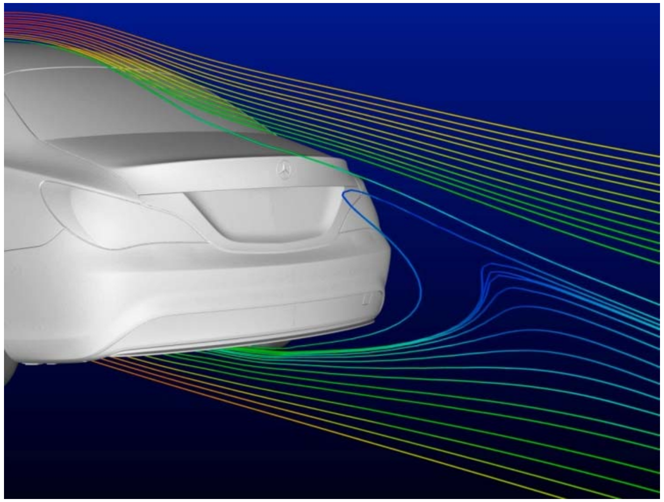
BOEING's LAMINAR FLOW PATENTS
& THE 787-9 LAMINAR FLOW SYSTEM
(US7866609, US8245976, US8783624)

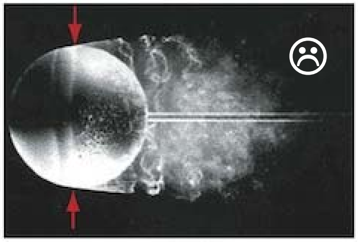
Laminar Flow Control

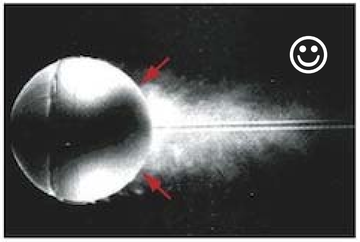
- Many experimental airplanes (B-18 at Langley, Vampire at Handley Page, F-94 & X-21 & JetStar & F-16XL at Edwards, 757 at Boeing… [*]), installed many tiny holes and/or slots over the skin, suction systems to suck the boundary layer air into the holes: "boundary layer suction" providing "Active Laminar Flow Control".
- Some (F-14, F-111…) looked at the impact of acoustics, wing sweep, contamination, etc.,on the transition from laminar to turbulent. [*]
- The X-21 Aimed to reduce wing viscous drag by 25%. However, reduction in drag barely worth the weight and power required for the suction system. Also, holes kept getting clogged with dust, debris, bugs, etc.
- Boeing has overcome all these difficulties and installed a Laminar Flow Control on all three tail fins of the 787-9. This technology will also be used on the 787-10, 777X, and probably other future airplanes.

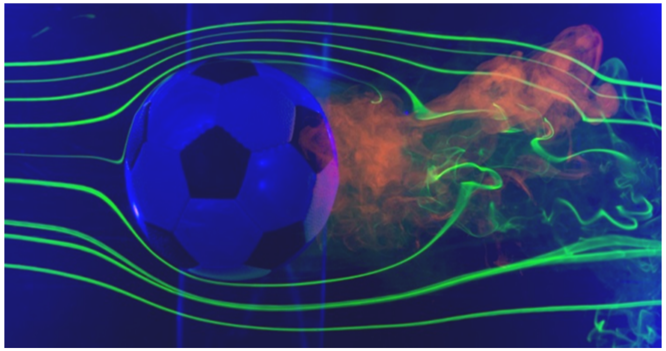
[* = http://www.nasa.gov/centers/dryden/pdf/88792main_Laminar.pdf]

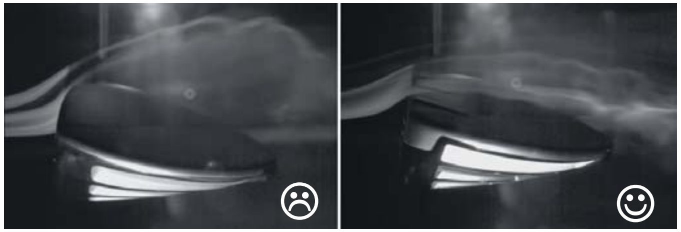
Separation Drag

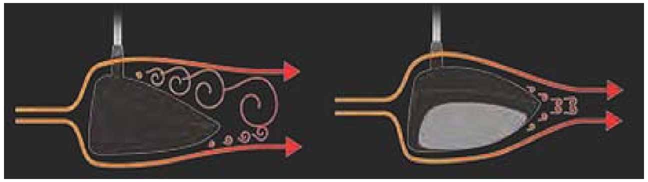


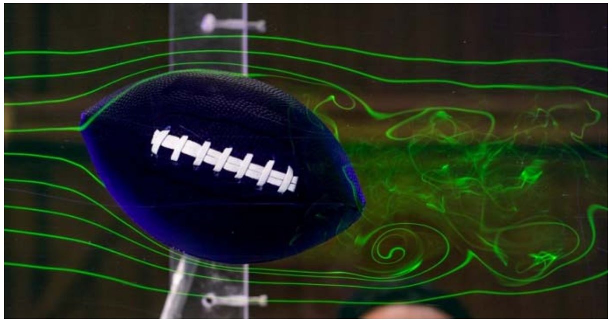








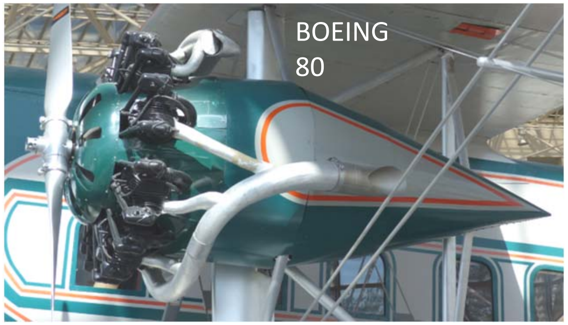


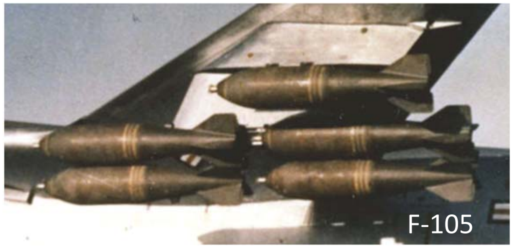


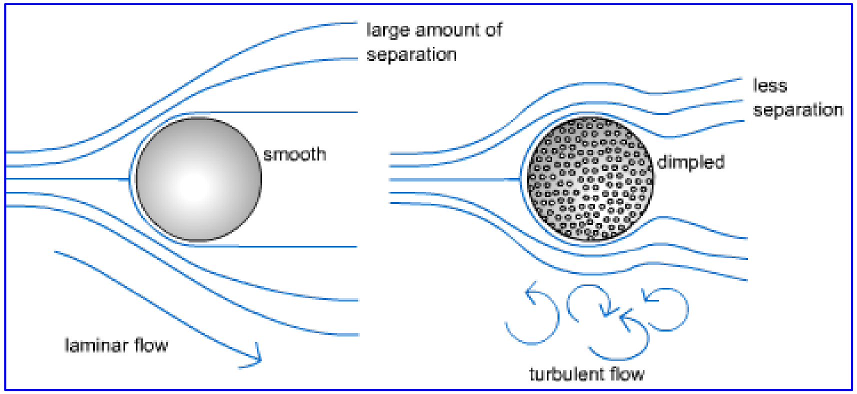
Separation Drag (Pressure Drag)

- "Pressure drag" happens **whenever the air around the front surfaces is at a higher pressure than the air around the aft surfaces**. This is normally very low… unless there is flow separation such as around a bluff body, i.e. non-streamlined shape, such as a car or ball. Separation drag is bad news! Manufacturers of sports gear and efficient cars work hard to minimize it. Must keep the flow attached, prevent separation, for as long as possible!
- This only **happens around areas where the surface recedes from the airflow too steeply for the air to "make the turn" and follow the surface**.
- The vast majority of drag on cars, sports balls, skiers, and other everyday objects, is pressure drag.
- On airplanes, this has been **almost entirely eliminated,** except during the stall, and on a handful of "draggy" features such as wires, exposed landing gear, and non-teardropped tails e.g. G.91, B-52, 737, 747 (right):

Reducing Separation Drag

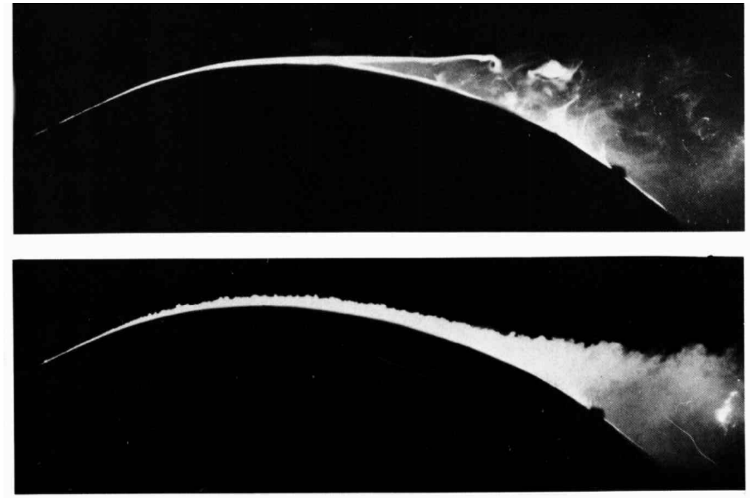




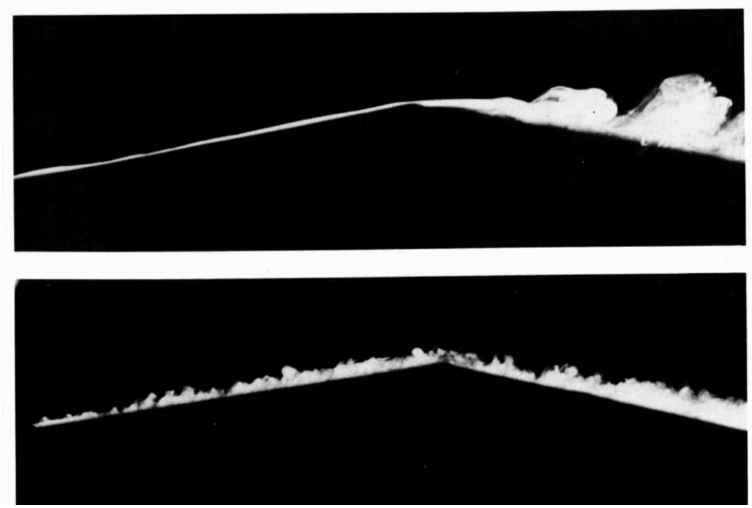


Reducing Separation Drag

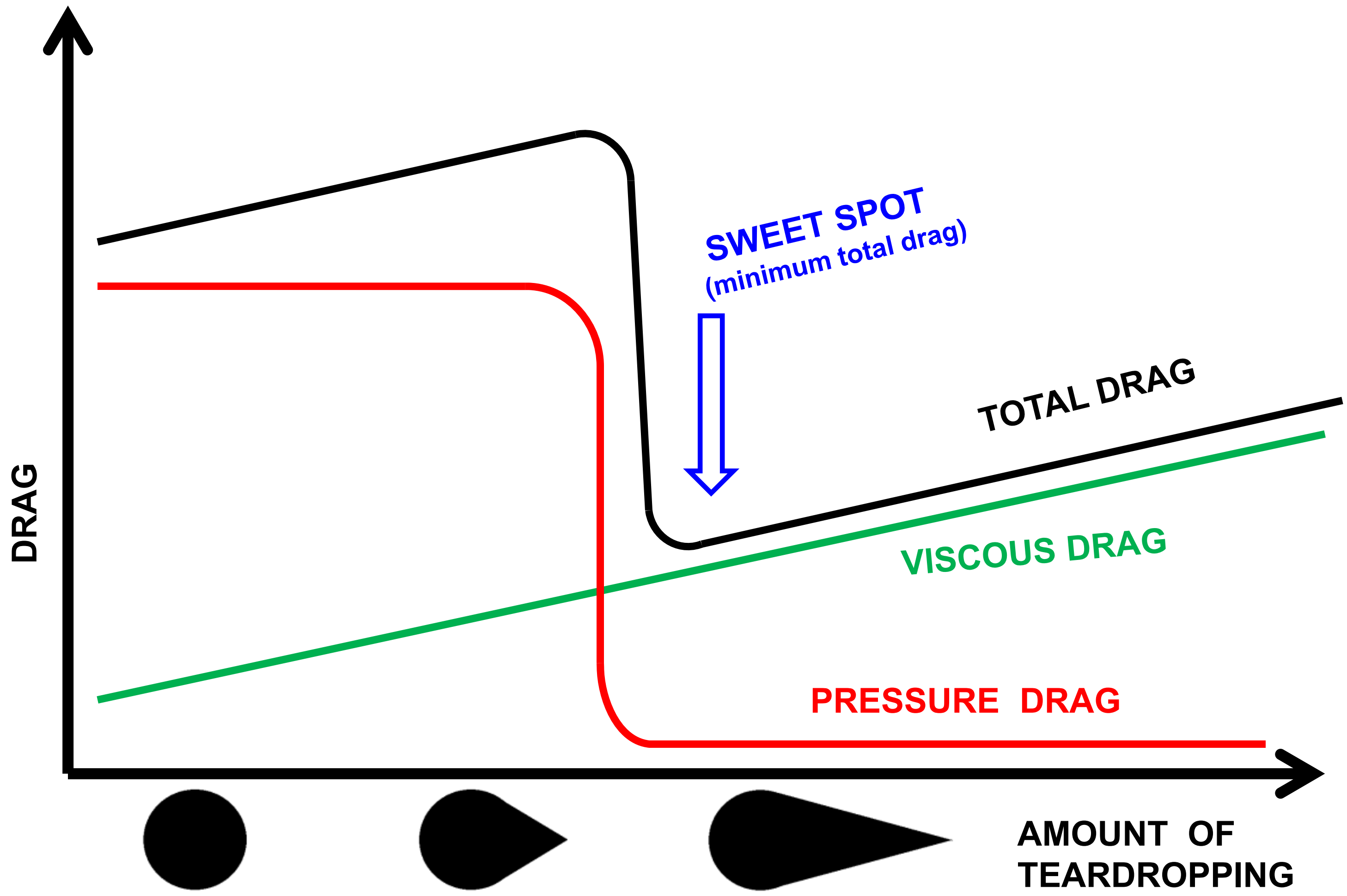
- The key way to minimize separation drag is “teardropping”: If surfaces recede from the airflow more gradually, the airflow won’t separate. Hence “canoe fairings” around airliner flap mechanisms, “wheel pants” around fixed landing gear, pointy tapering tail cones, teardrop-shaped bombs and external tanks, etc. As the surface of an airplane component is gradually changed from “bluff body” to “tear-dropped”: When the angle at which the surface recedes from the air becomes shallow enough, the airflow will change from “separated” to “attached” and there will be a drop in pressure drag.
- One ***other*** way to prevent separation is to roughen up the air: Turbulent air is more viscous, more “sticky” (see right). Airplanes with non-pointy tail cones often have vortex generators ahead of where their surface slopes away, and golf balls have dimples for the same reason. VGs and dimples increase viscous drag, but lower overall drag (because without them, pressure drag becomes very high on bluff bodies, i.e. on non-teardropped things like golf balls, blunt tail cones, and most cars).



156. Comparison of laminar and turbulent boundary layers. The laminar boundary layer in the upper photograph separates from the crest of a convex surface (cf. figure 38), whereas the turbulent layer in the second photograph remains attached; similar behavior is shown below for a sharp corner. (Cf. figures 55-58 for a sphere.) Titanium tetrachloride is painted on the forepart of the model in a wind tunnel. *Head 1982*



Reducing Separation Drag



Reducing Separation Drag

At what angle do you teardrop?

- Teardropping any more than necessary will add surface area, and thus viscous drag, and also weight and thus induced drag, for no good reason. So the optimal amount of teardropping is such that, if you teardrop any more, the reduction in pressure drag will be canceled out by increases in viscous drag due to added area and in induced drag due to added weight.
- The optimal angle will depend on the Reynolds number, a function of the airspeed and also of the size of the part. The definition of Reynolds number is **$Re=\rho VL/\mu$** where ρ is density, V is speed, L is length, and μ is the fluid's viscosity. The Reynolds number is basically the ratio between the air's momentum and its viscosity: Small airplanes traveling slowly experience low Reynolds numbers (one extreme: The mechanics of bumblebee flight are different from airplane or even bird flight, because insects effectively "swim in honey") and large airplanes traveling fast experience high Reynolds numbers. The faster you fly, and the larger your part is, the shallower (pointier) a teardrop angle you will need in order to eliminate separation. (For this same reason, smaller/slower airplanes can have curvier wings without stalling).Engineers know what the optimal teardropping angle is as a function of the Reynolds Number (i.e. depending on the size of a component and of how high and fast it will fly most of the time).
- So the wheel fairings around the small landing gear of slow-ish single-engine airplanes are less "pointy" than the canoe fairings around large flap mechanisms of fast-ish jetliners.

Induced Drag

Angle of attack

Vorticity

Induced Drag

Induced drag is also known as "drag due to lift".

The more lift an airplane has to generate (because it is heavier, and/or because it is pulling Gs), the more drag-due-to-lift it will generate.

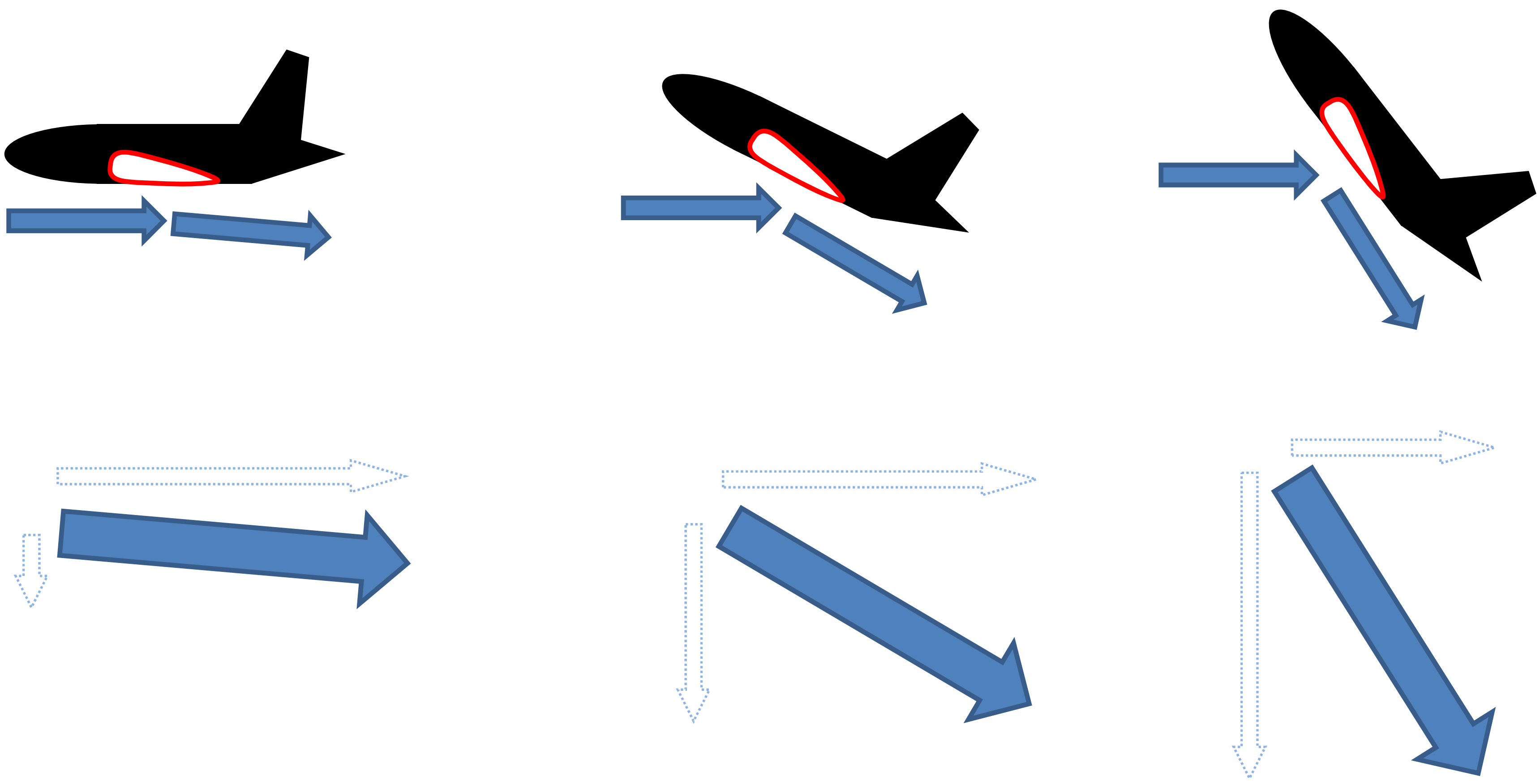
Induced drag is caused by two things:

- One is drag due to angle of attack. The higher the angle of attack, the higher the drag on the wings.
- The other is spanwise flow, which corresponds to the vorticity. The higher the spanwise component of flow over the wings (i.e. the more intense the wingtip vortices), the higher the drag on the wings.

Why is that? We will see.

Note: Technically, the “drag due to angle of attack” is a kind of pressure drag. In a textbook about aerodynamics or about airplane performance, “induced drag” is only the drag due to spanwise flow. However, here I will lump “drag due to angle of attack” into my description of induced drag. I will do this because the ways to reduce both of these kinds of drag are the same, and because the reason why spanwise flow causes drag is the way that spanwise flow requires an increase in angle of attack, thus increasing the drag due to angle of attack. So, these two phenomena are closely related.

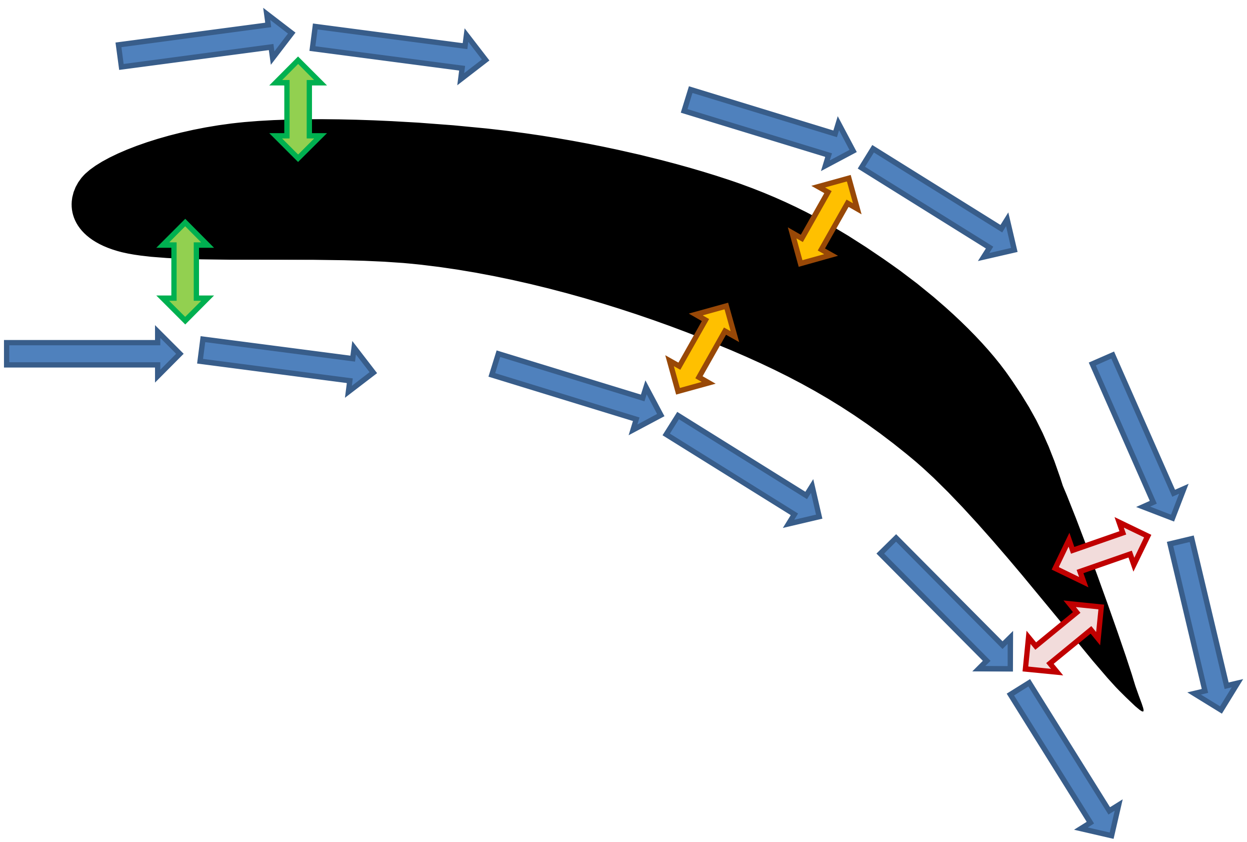
Drag Due to Angle of Attack



Drag Due to Angle of Attack

- A wing deflects air downwards.
- However, if the air maintains its speed (i.e. the magnitude of its velocity vector) when it is deflected downwards, this means that a gain in the downwards component of the velocity will be related to a loss in the backwards component in the velocity.
- In other words, the more steeply the air is deflected downwards, the more it is slowed down by the airplane.
- Air that is deflected 90 degrees downwards would have no horizontal velocity relative to the airplane.
- How exactly does this slow the airplane down? (Other than the abstract "equal and opposite force" law?)

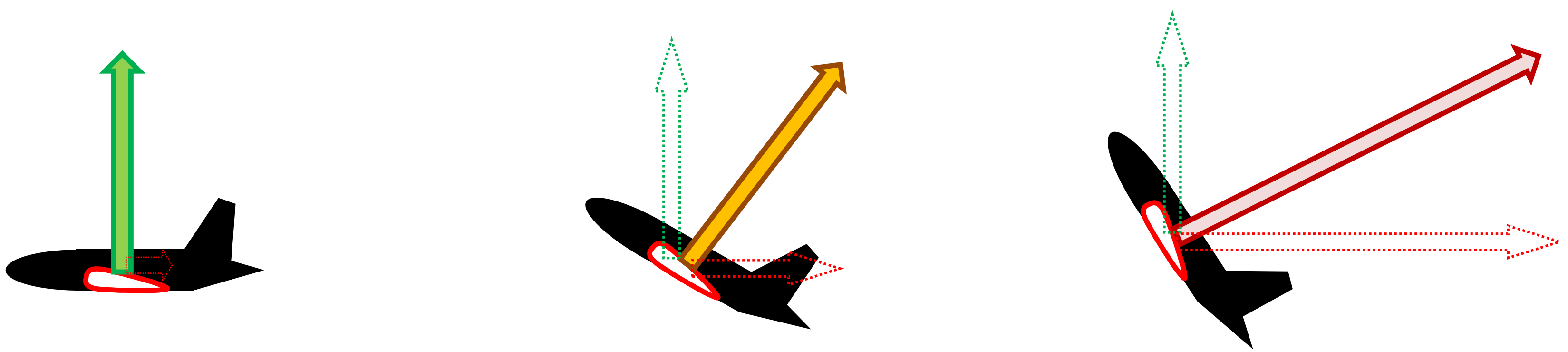
Drag Due to Angle of Attack



Drag Due to Angle of Attack

- The pressure force between the air and the wing is perpendicular to the surface of the wing, perpendicular to the direction along which the airflow is going.
- When the airflow is roughly horizontal (e.g. where the wing first starts to deflect the airflow slightly downwards), the pressure force is vertical.
- But when the airflow becomes slightly diagonal, deflecting it further downwards requires a force that is now slightly off the vertical, including a horizontal component that pushes/pulls the airplane into the direction of the airflow, against the direction of flight.
- When the airflow becomes very diagonal (close to vertical, e.g. near the back of a flap that has been deployed at a steep angle), the force it makes on the wing becomes almost entirely horizontal. When air is flowing that steeply, it takes a lot of drag (horizontal force) to generate just a little lift (vertical component of the force, that comes from deflecting the air downwards).
- It’s like a ball bouncing off of a wall. When the ball changes trajectory, the force required to change its trajectory will be perpendicular to the surface of the wall, roughly perpendicular to the average velocity of the ball. The more vertical the path of the ball, the more horizontal the force between the ball and the wall.
- Yes, here we are neglecting friction / viscous forces.

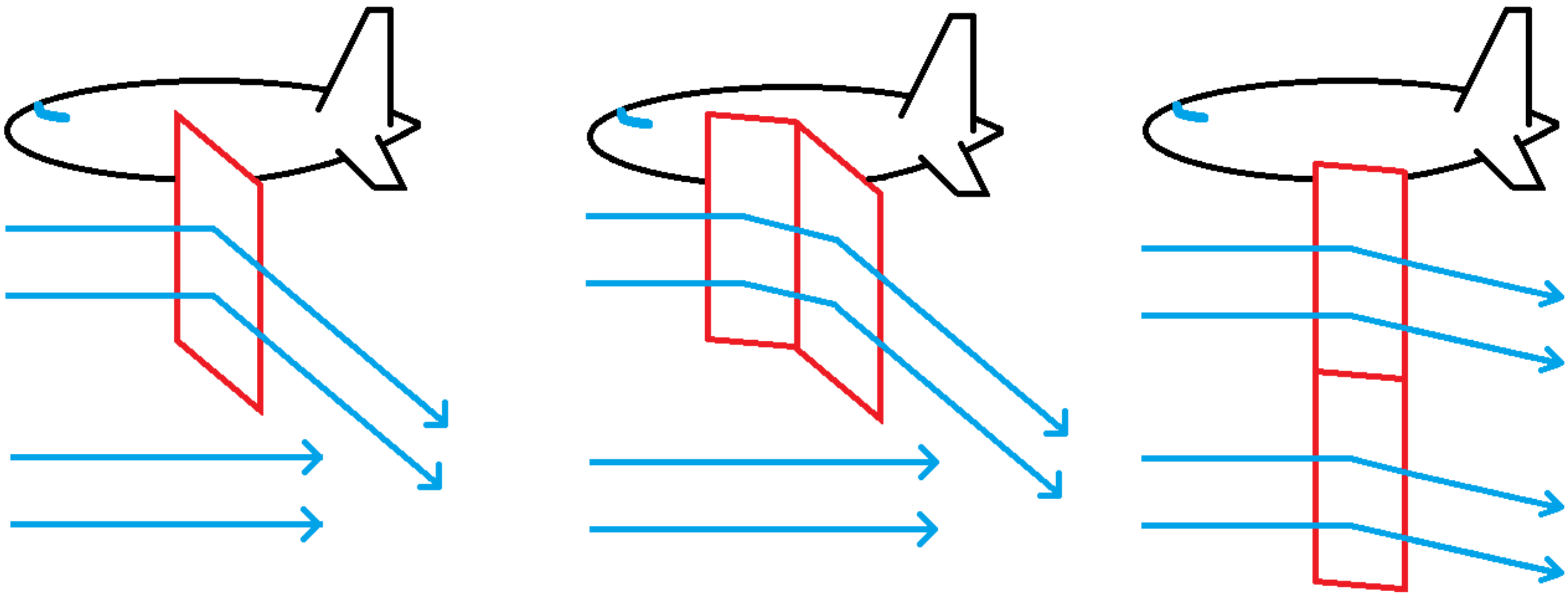
This is worse at slow speeds!



This is worse at slow speeds!

- You may think that all kinds of drag get more intense when an airplane is flying faster, and reduce when an airplane is flying more slowly.
- However, this phenomenon we are currently discussing gets worse when an airplane flies more slowly, because a higher angle of attack is required.
- (Why is a higher angle of attack required when an airplane flies more slowly? We discussed this during the lift section: Lift is dynamic pressure times wing area times the coefficient of lift. When speed goes down, dynamic pressure goes down. So in order to make enough lift to keep the airplane in the air, we need more coefficient of lift. This means increasing the angle of attack, and/or deploying high-lift devices such as flaps and slats. Or, perhaps more intuitively: If a wing interacts with fewer air molecules per second – which it will when the airplane slows down – then it must deflect those fewer air molecules downwards more steeply in order to generate enough lift to stay up in the air).
- The vertical component of the lift force is equal to the weight of the airplane. However, the more the airplane "tilts back", the greater the component of "lift" pointing in a backwards direction. This means: (1) More drag. Also, (2) Even ***more*** angle of attack is needed, to make even more lift, because the ***vertical*** component ***alone*** must equal the weight of the airplane!

How to reduce "drag due to angle of attack"?



More wingspan!

How to reduce "drag due to angle of attack"?

- How can we reduce this "drag due to angle of attack"?
- First of all: **Lighten up the airplane!** The less heavy it is, the less alpha is needed to make enough lift to fly, and the less drag there will be (so the more fuel-efficient the airplane will be).
- Secondly (and counter-intuitively): **Fly more quickly!** (Of course, if you fly more quickly, you get more viscous drag. So there is some intermediary "sweet spot" speed, where the ***sum*** of the viscous drag and the induced drag are minimized. More about this later).
- Most interestingly: **Maximize the wingspan!** That is what the graphic in the previous slide shows. Say that you are designing an airplane, and the wing area right now is too small. You want to make the wing bigger. You have two options: (1) add some wing area to the trailing edge, or (2) add some wing area to the tip.
- If you add some wing area to the trailing edge, thereby increasing the wing chord (distance from the leading edge to the trailing edge), that added area sits in downwards-moving air from the previously-existing wing. The added area is in downwards-moving air, and must be at a higher angle of attack in order to deflect that air even more steeply downwards. So the lift from that area will be more "off-vertical".
- (Actually, in reality, simply increasing the chord will mean that the pre-existing part of the wing will fly at a slightly lower angle of attack than before, so that the pressure field retains the same shape/distribution but gets bigger. So simply increasing the chord of a wing will not increase – or even change – the "drag due to angle of attack").
- If you add some wing area to the wing tips, thereby increasing the wingspan (distance from one wingtip to the other), that added area sits in "fresh air" that the previously-existing wing was not influencing. The added area is in horizontally-moving air, and can be at a lower angle of attack than the rest of the wing while still deflecting that "fresh" air downwards. So the lift from that area will be almost vertical, with very little drag (very little horizontal/backwards component).
- In short, the "drag due to angle of attack" does not depend on wing area or on wing chord, it simply depends on the wingspan. So, given that you want a certain wing area to make enough lift for your airplane, maximizing the wingspan means maximizing the aspect ratio…

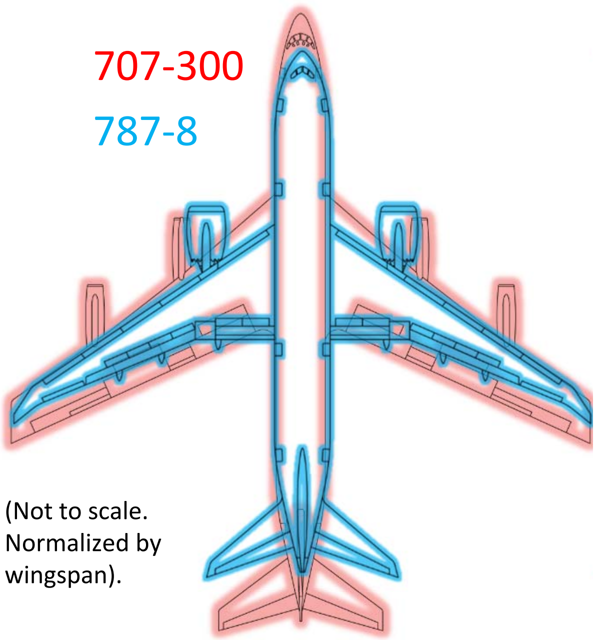
Aspect Ratio

777X

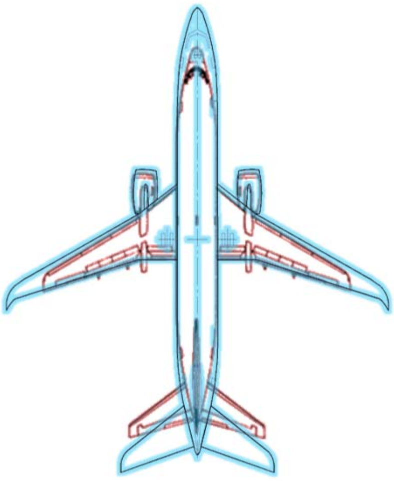
Schleicher ASH 30

707-300

787-8



(Not to scale.
Normalized by
wingspan).



737-200

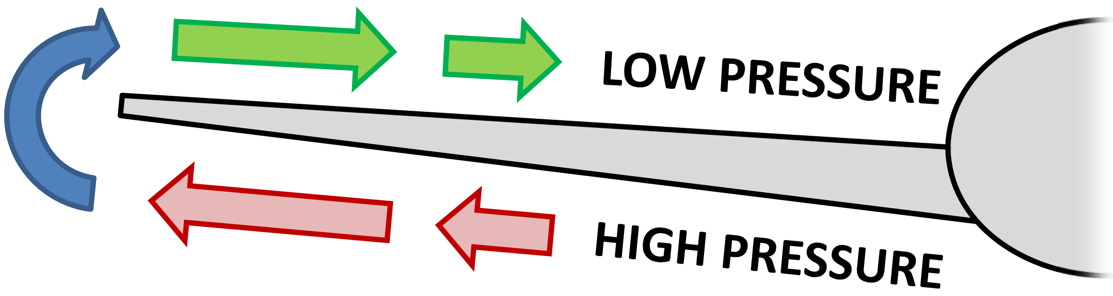
737-800

(To scale)

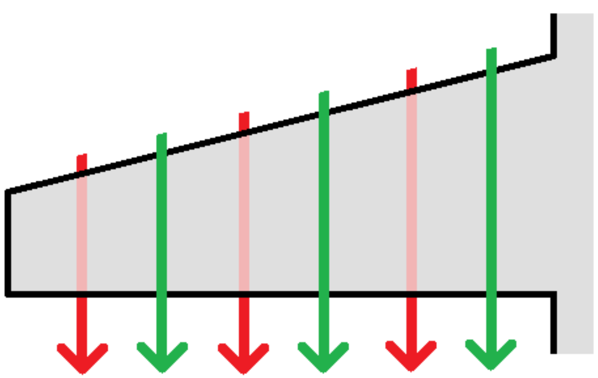
Aspect Ratio

- The best way to reduce "drag due to angle of attack" is to increase the wing aspect ratio.
- The aspect ratio is the wingspan divided by the average chord. (The average chord is the wing area divided by the wingspan… so the aspect ratio can be calculated as the wingspan squared divided by the wing area)
- So why don't all airplanes have glider-like wings? Because airliners have to fit between gates, and small propeller airplanes have to fit in hangars that are between 40 and 45 feet wide.
- Another reason: Higher-wingspan wings are structurally heavier. More lift happens further from the fuselage, causing a higher bending moment, requiring stronger (and thus heavier) structure at the wing root. So, past some wingspan, you start gaining more induced drag from the heavier weight than you lose from the higher aspect ratio.
- Thanks to better structures engineering, and technologies like Maneuver Load Alleviation, higher aspect ratios are practical: The 707 wing aspect ratio was seven; the original 737's was around nine; the 787's is around 10, and the 777X… will need folding tips to fit at the gate!

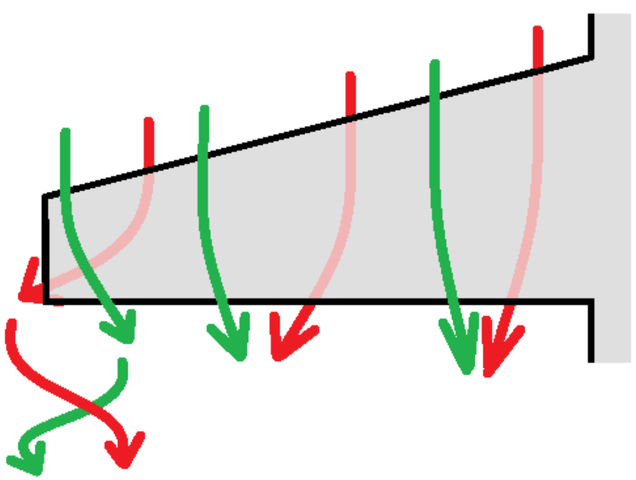
Spanwise Flow



High speed flight:



Slow flight:



Spanwise Flow

- The high pressure under the bottom of the wing pushes air outwards, away from the centerline of the airplane (i.e. away from the plane of symmetry, where the fuselage is).
- The low pressure over the top of the wing "sucks" air inwards, towards the centerline of the airplane (i.e. towards the plane of symmetry, where the fuselage is).
- This is especially bad while the airplane is going more slowly. At high speeds, the air has more inertia, so a given pressure difference will not deflect it by as high an angle. But at slow speeds, the air is influenced by this pressure difference for longer, and can be turned more tightly (because, at a slower speed, a given centripetal force can achieve a tighter turn radius).
- Like the deflection caused by the wing in the vertical plane, this deflection on the horizontal plane causes the air to lose some of the backwards component of its velocity. In other words, this "stirring up the air" causes it to slow down locally.
- So if the airplane is flying through locally-slower air… it will need a higher angle of attack in order to generate lift. This worsens the "drag due to angle of attack".

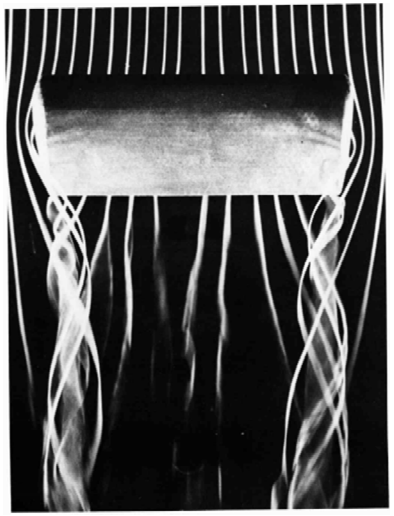
- Again: Only the drag caused by spanwise flow (i.e. the increase in "drag due to angle of attack" caused by the increase in angle of attack required by how the air is being swirled around spanwise) is technically called "induced drag" in textbooks about aerodynamics or about airplane performance. By that definition, an infinite wing has no induced drag. However, here I lumped "drag due to angle of attack" into my description of induced drag, because these two things are so closely related, because one is basically an increase in the other, and reducing one will also reduce the other. For beginners, I believe that my way is more intuitive.

Wingtip Vortex

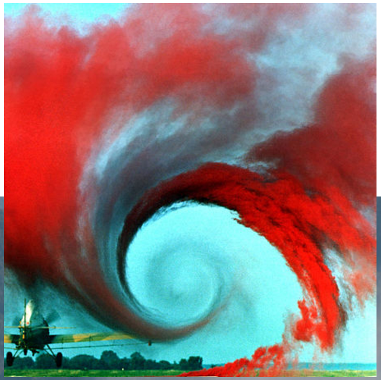
C-130

757

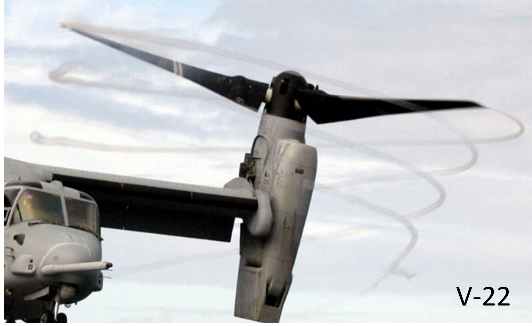
F/A-18



C-27



PZL-106



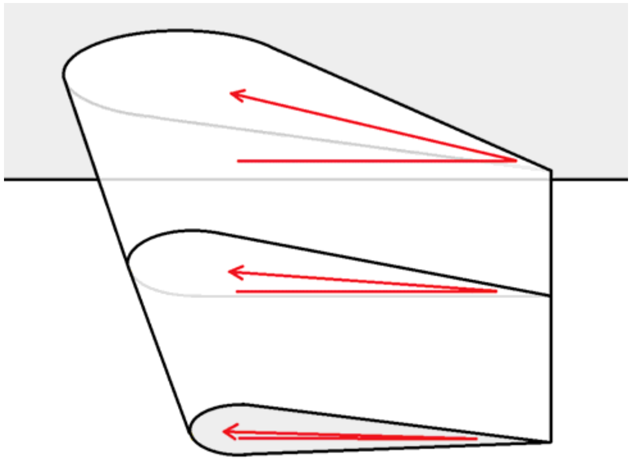
V-22

Wingtip Vortex

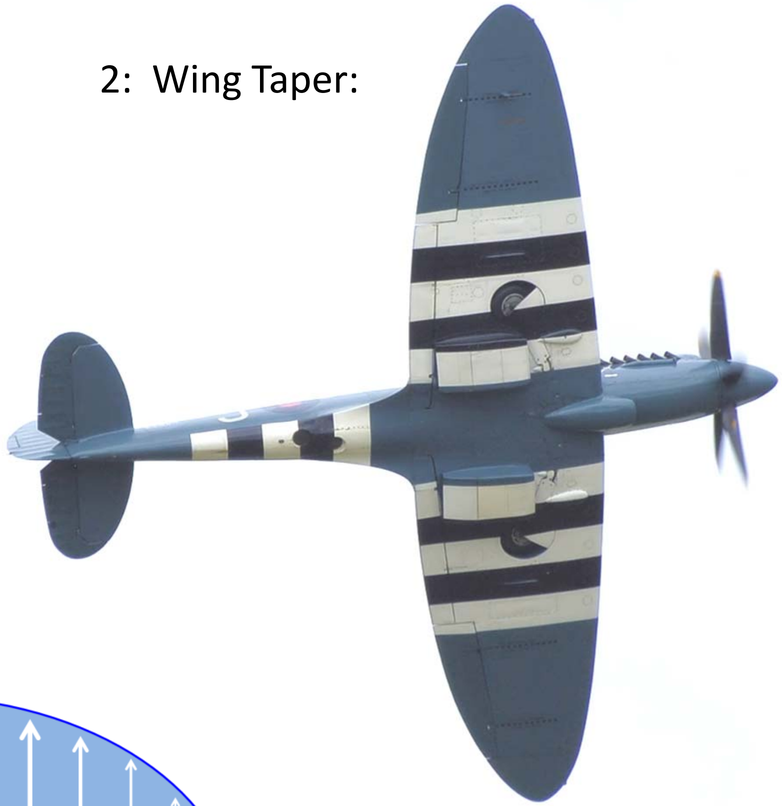
- The clearest symptom of spanwise flow is the wingtip vortex.
- As high-pressure air from under the wing “spills” around the wingtip, being “sucked” by the low-pressure air on top of the wing, a persistent tornado-like vortex is formed, and trails the wingtip.
- This can be observed not only in wings but in anything that makes lift, e.g. rotor blades and propeller blades.
- How can this be reduced? One way is to increase the wingspan. A high wingspan means there is a longer distance from the bottom of the wing, around the wingtip, to the top of the wing. Longer wingtips act like a fence, blocking the action of the pressure differential. (Technically, it is a pressure *gradient* that moves the air. Air flows from high pressure to low pressure. If the wing is bigger, then the pressure changes more gradually – i.e. less pressure change per foot – as one moves from the fuselage to the wingtip. So the longer the wingspan, the more gradual the pressure change along the wingspan, and the less the air will be deflected along the span). An infinite wing (or a 2D airfoil section in a 2D wind tunnel or in a 2D analysis) does not experience spanwise flow.

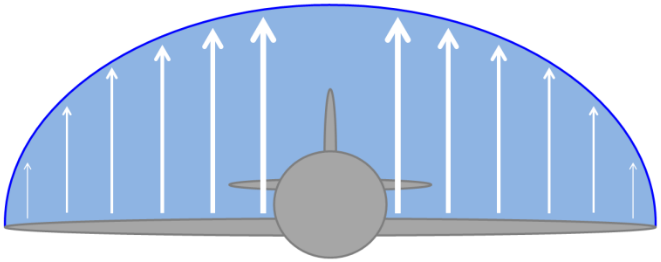
Reducing Spanwise Flow: Lift Distribution

1: Wing Twist a.k.a. WashOut:



2: Wing Taper:





The decrease in chord times the decrease in angle of incidence, along the wingspan, should equal an **elliptical distribution of lift force** along the wingspan

Reducing Spanwise Flow: Lift Distribution

Another way to reduce spanwise flow is to distribute the lift so that **more of the lift happens inboard**:

- **Twist the wing**: Lower angle of incidence at the wingtip. (This is also good for stall characteristics, as we have discussed).
- **Taper the wing**: Make the chord (the distance between the leading edge and the trailing edge) be narrower at the wingtip.

In a way, the wingtip is there less "to generate lift" and more "to keep the air under the wing from spilling over onto the top of the wing". If the wingtip is at zero angle of attack, generating no lift, then induced drag will be reduced. (This is also good for reducing structural weight, because it lowers the wing bending moment if more of the lift is further inboard rather than near the tips. And, it prevents tip stall!)

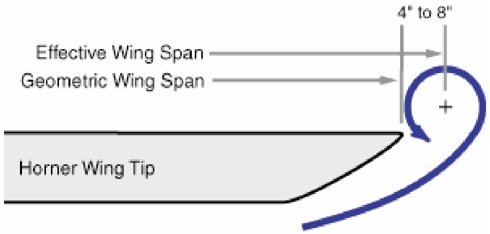
The lift distribution (how much lift is generated where along the wingspan) with the lowest induced drag is: **Elliptical**. This is usually achieved with a combination of twist and taper. (On the Spitfire, it's almost only taper!)

$$Cd_i = \frac{Cl^2}{\pi \ AR \ e}$$

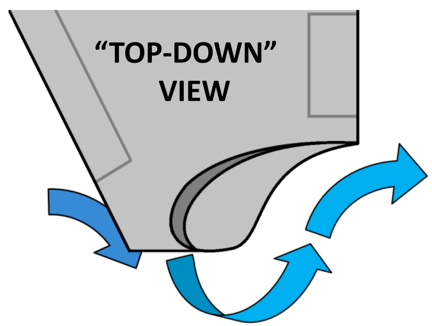
Here is the actual equation for the coefficient of induced drag. AR is the aspect ratio, and "e" is how close to elliptical the lift distribution is: e ≤ 1
(1 for a perfectly elliptical distribution… typically less)

Reducing Spanwise Flow: Wingtip Devices

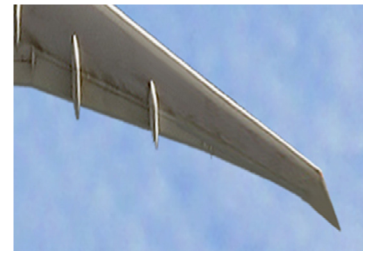
HOERNER TIPS
(S-19, HR200)

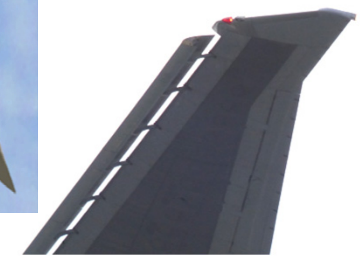


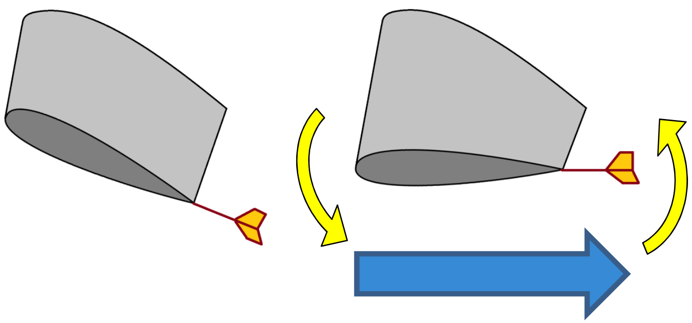
WINGLETS (737, MD-11)



RAKED WINGTIPS (777, 787)







Reducing Spanwise Flow: Wingtip Devices

- Sighard F. Hoerner was the first to systematically study, in wind tunnels, the impact of the wingtip shape on drag. (Previously, wingtips were designed by "gut feel"). His conclusion, published in a USAF paper in 1952: An upwards-sloped wingtip pushes the vortex further away from the wingtip, effectively extending the wingspan by several inches and increasing the wing's aspect ratio, lowering induced drag. Such "**Hoerner wingtips**" can still be found today in many small airplanes.
- Big breakthrough in 1970s (Whitcomb, at NASA): **Winglets** can act like sails. They sit in the air that spills inboard over the wingtip (and sometimes in the air that spills outboard from under the tip) and deflect that air backwards, pushing themselves forwards: Less induced drag, more "thrust".
  - Two feet of winglet height will reduce the induced drag about as much as a one-foot increase in span… but with less wing bending. And the airliner still fits between gates at the airport. (So, in business jets, winglets are arguably for "cool factor").
- **Raked wingtips**…
  - One way to think about how they work: They act like a little tail boom for the wingtip: Swept and not very stiff, the airflow twists them closer to the horizontal plane, keeping the angle of attack of the wingtip closer to zero.
  - Another way to think about it: More trailing edge length means vorticity is more spread out. More sweep gives you more trailing edge without more span (i.e. without more bending).
  - Some sources claim raked wingtips are most beneficial for longer flights (i.e. in cruise rather than during climb or descent) and less prone to icing issues than winglets, but I have not seen solid data or a convincing theory.

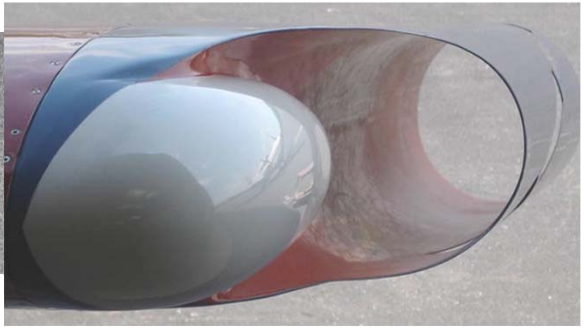
Boeing has published a really terrific paper about how winglets and raked wingtips work, how they are designed, etc: http://www.smartcockpit.com/docs/Wingtip_Devices.pdf

Futuristic Wingtip Devices?

SPIROID WINGLETS (FALCON 50, GULFSTREAM 2)

WING GRID (STEMME S10, DYNAERO MCR-01)

MINIX WINGTIP (RV-8)



Futuristic Wingtip Devices?

Newer ideas currently being tested include:

- Spiroid wingtips
- Wing grid
- Minix wingtip

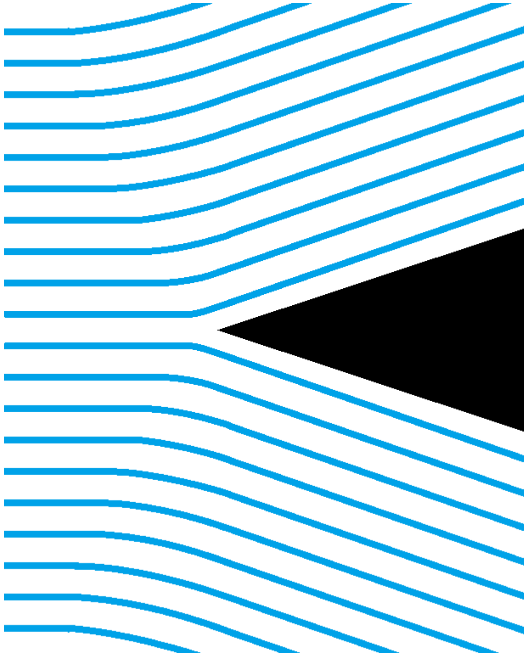
How do they work? I have no idea…

(Their design might be based in a misunderstanding of induced drag – e.g. on the wingtip vortex being the cause of the problem, rather than another symptom of the same problem – rather than on good fluid mechanics).

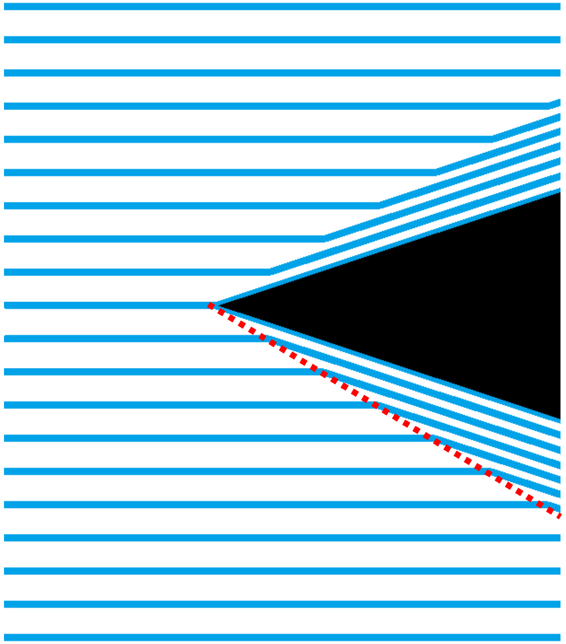
But… they're out there, FWIW.

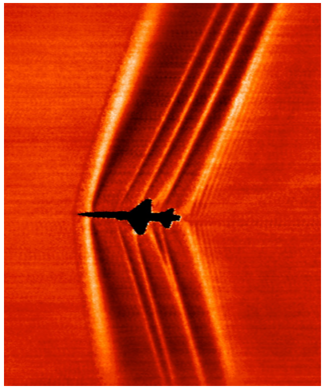
Wave Drag

M<1 (subsonic):



M>1 (supersonic):





“action at a distance”

(i.e. air starts moving out of the way before airplane arrives)

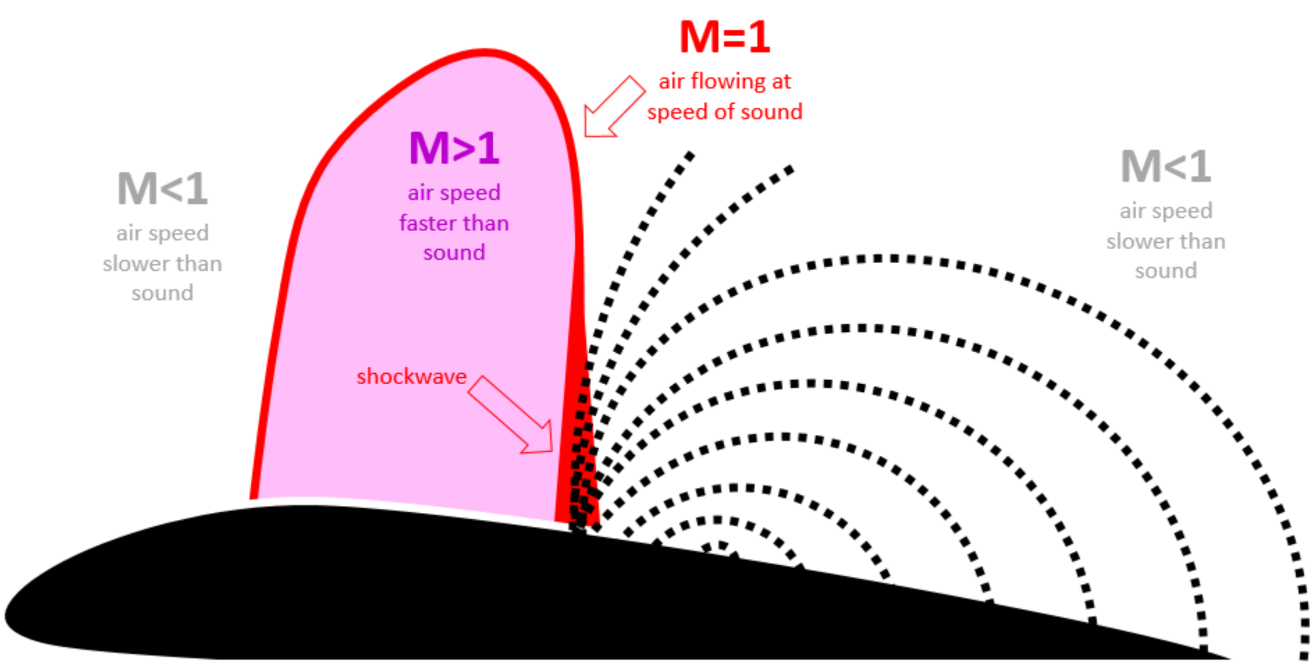
shockwaves

(i.e. air shoved out of the way at last second, then moves next layer out of the way)

Wave Drag

- When a body flies through the air at subsonic speeds, it gently pushes the air out of the way before the air arrives.
  This is done via pressure, which travels at the speed of sound.
- While flying through the air faster than sound, **the air does not have "time to get out of the way"**. The air right next to the body gets shoved out of the way, and then shoves the next layer of air, which shoves the next layer of air…
- This causes **shockwaves** to form. These are abrupt changes in air density and pressure. (Subsonic airflow is essentially incompressible). At the shockwaves where pressure and density go up, temperature goes up. All this energy comes from the airplane! Lots of additional drag once at speeds where air becomes compressible (i.e. "wave drag" a.k.a. "compressibility drag")
- To watch a very good video that demonstrates the concepts in the next eight slides (130 to 137) including footage of airplanes and wind-tunnel tests, see https://youtu.be/EQTiSxLwwPo .

Wave Drag and Wings

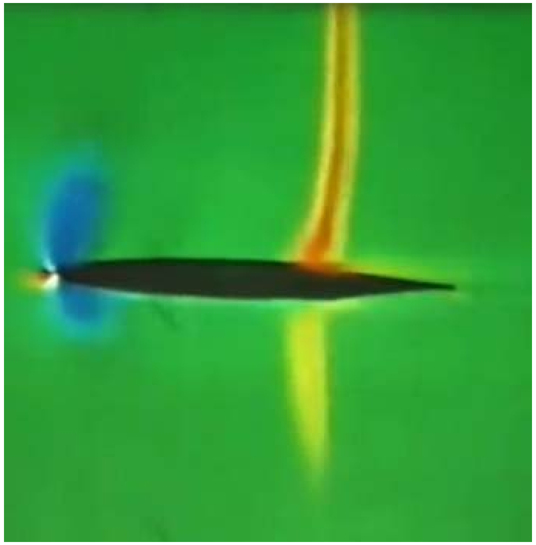


Wave Drag and Wings

All points on a wing make a little "whooshing" sound when air goes over them. The sound emanates as pressure-wave ripples in every direction, at the speed of sound, from every point on the airplane surface.

If all airflow is subsonic, then the sound ripples travel in every direction, including forwards over the wing, and out past the leading edge. From the point of view of the airplane, the ***forwards***-traveling ripples travel at the speed of sound ***minus*** the airspeed, while the ***backwards-***traveling ripples travel at the speed of sound ***plus*** the airspeed.

Wings are "special": Air speeds up over the top of the wing during flight. So as the airplane speeds up and reaches (typically) Mach 0.7 or 0.8, airflow over a region of the wing becomes supersonic, before the airplane reaches Mach 1. A "bubble" of supersonic air appears over the wing.



When the pressure waves (sound ripples) from the aft wing upper skin travel forwards, towards this supersonic bubble, they cannot get past the back surface of the supersonic bubble, the area where the airspeed is Mach 1. (It's like they're trying to walk the wrong way up an escalator or treadmill; trying to travel forwards at the speed of sound through air that is going backwards at the speed of sound). So all the air pressure, all the sound ever made by the back of the upper wing, builds up along the back edge of the supersonic bubble.

This creates a shockwave, a thin "sheet" of very dense, very hot air.

This causes lots of drag, among other problems. It is the start of the "sound barrier".

A given wing, making enough lift to keep the airplane in the air, will start experiencing supersonic flow over the top (and, thus, making this shockwave) while flying at some critical speed less than Mach 1 (again, typically 0.7 or 0.8, sometimes even less if it's a particularly thick wing). That speed is the wing's "Mcrit".

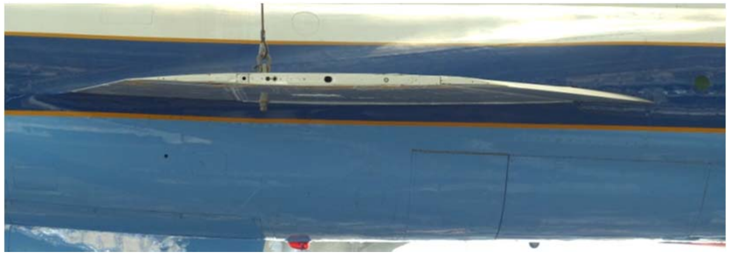
The key question here: If we want to cruise at, say, Mach 0.85, how do we design a wing so that its Mcrit is higher than 0.85? What can we do to a wing's design to get Mcrit closer to a value of 1?

Visible Shockwaves

Visible Shockwaves

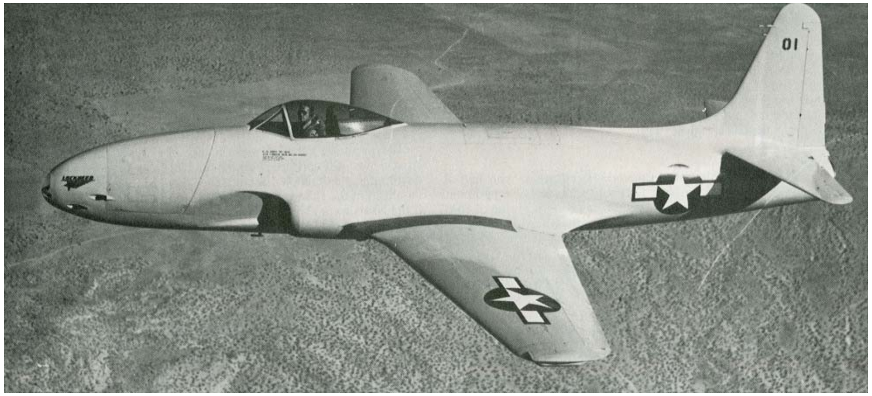
737 wing, 767 engine

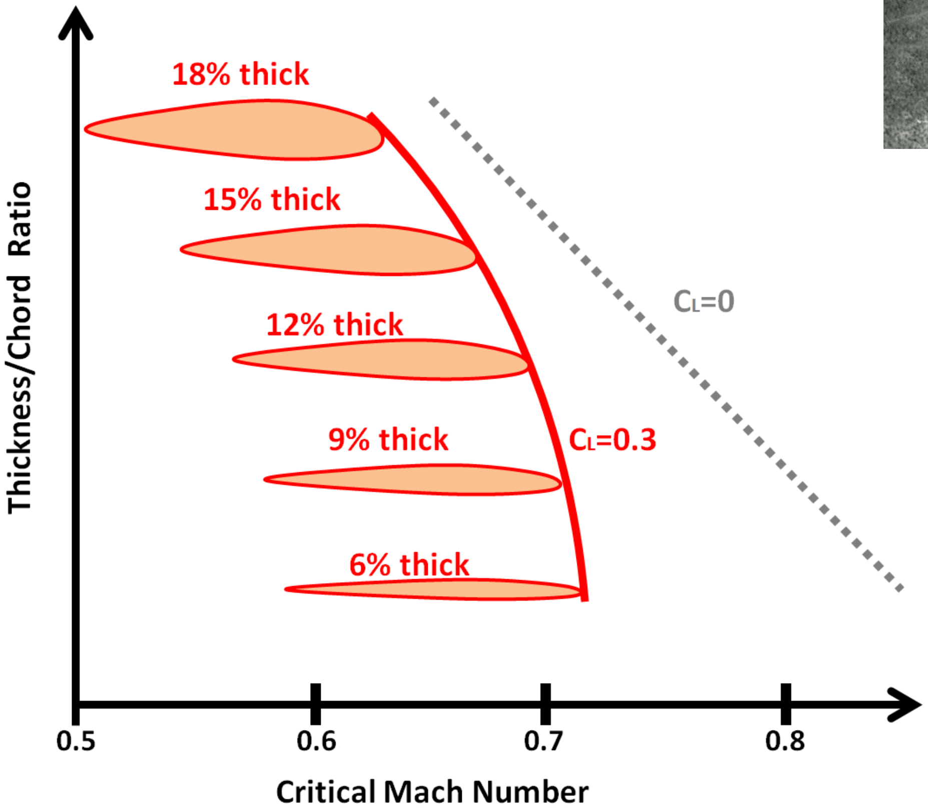
Delaying the Onset of Wave Drag, 1: Thin Wings

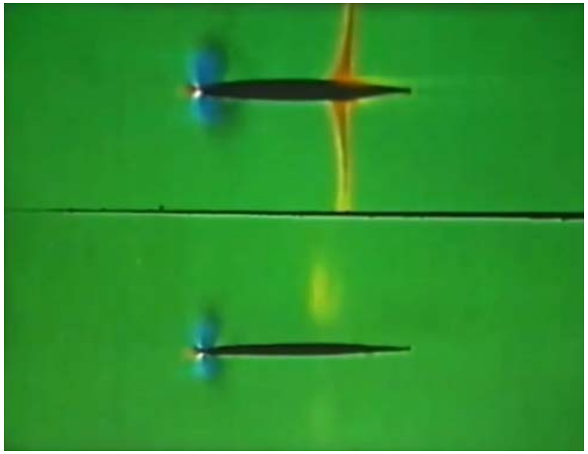


F-104

P-80







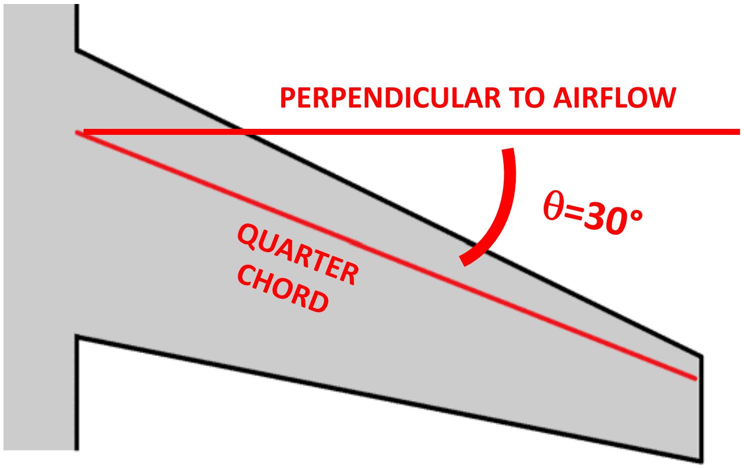
Delaying the Onset of Wave Drag, 1: Thin Wings

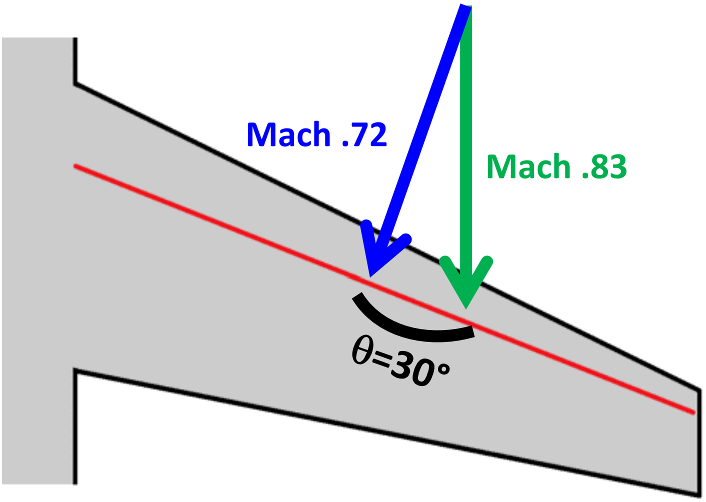
How can an airplane fly closer to the speed of sound without the air over the wing forming a shockwave?
How do we get Mcrit to be closer to M=1 (the speed of sound)?

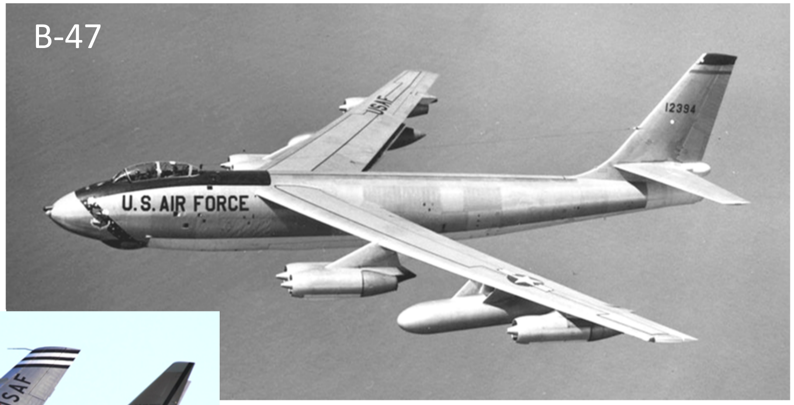
Thinner wings:

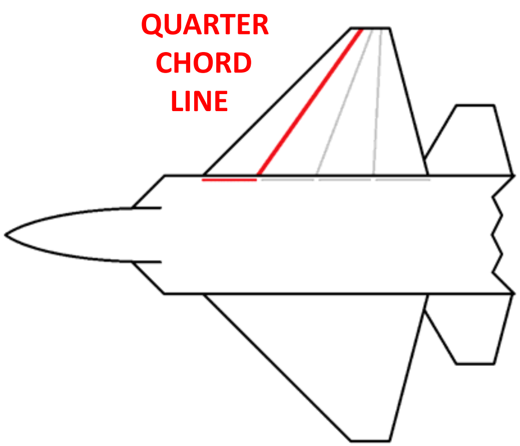
- This was the key discovery in the 1940s that allowed the first airplanes to get close to the sound barrier.
- However, they stall easily and abruptly, requiring fast landing speeds and long runways. Many structural difficulties as well.
- The P-80 was the first airplane (1944) to implement this feature. Thin wings allowed the P-80 to fly much faster than any other airplane at the time. It could fly that fast with only a standard amount of thrust, no need to dive or to use rocket engines.
- The green image in the previous slide shows two wind tunnel photographs shot through a material that is sensitive to air pressure and density. The red regions show air being compressed to high pressure, density, and temperature. Both wings are flying at the same speed. The thick wing on top already has clear shockwaves, including one off the bottom surface. The thin wing at the same speed shows barely any shockwave effects at all. See https://youtu.be/EQTiSxLwwPo for a video of this and other experiments in a trans-sonic tunnel.

Delaying the Onset of Wave Drag, 2: Swept Wings









Delaying the Onset of Wave Drag, 2: Swept Wings

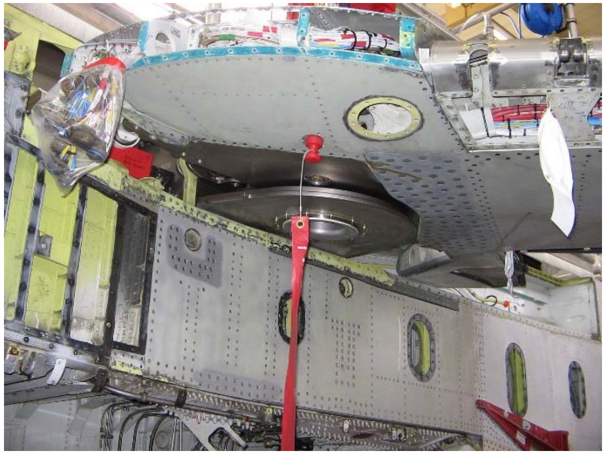
How can an airplane fly closer to the speed of sound without the air over the wing forming a shockwave?

How do we get Mcrit to be closer to Mach 1?

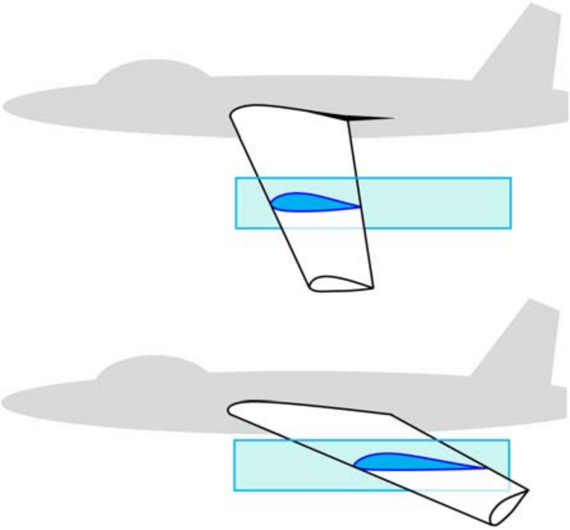
Wing sweep:

- Shockwave formation depends on the chordwise component of the flow. Sweep the wings by some angle, and the chordwise flow speed becomes the airspeed times the cosine of that angle. (Sweep the wings 37 degrees and your effective Mach number goes down by 20%! However, the actual increase in Mcrit never quite matches this theoretical result).
- One problem: Swept wing tips want to stall first, leading to reduced roll control.
- Another problem: Stalls cause pitch instability. The center of lift moves forward when the tips stall, which raises the nose even more, worsening the stall.
- Both of these problems are manageable thanks largely to wing twist and other anti-stall design features (e.g. wing fences in the early days).
- The effective sweep angle is that at the “quarter chord”, 25% of the way from the leading edge to the trailing edge, near the center of lift. So airplanes with unswept trailing edges (e.g. F-16, F-22, Mirage, Concorde) still have a lot of wing sweep.
- 1947: The F-86 was the 1st airplane to exceed Mach 1 (but could only do it in a dive).
  The B-47 could cruise transsonically with much less drag than any other large airplane.

[A brief digression: Swing Wings and Forward-Swept Wings]



TORNADO



Variable Geometry Wings ("swing wings")

e.g. X-5, F-111, F-14, B-1, MiG-23, MiG-27, Tu-160, Tornado, etc.

Advantages:
- At slow speeds, un-sweeping the wing means less induced drag (higher aspect ratio) and more lift (curvier airfoil).
- At high speeds, sweeping the wing gives the ability to pull more Gs (less wingspan = less wing root bending moment) and, of course, reduced wave drag by "flattening"/"stretching" the airfoil cross-section (more sweep).

Disadvantages:
- Weight of mechanism reduces useful load. (To carry a given useful load, a swing-wing airplane must be slightly bigger than a fixed-wing airplane).
- Complexity of mechanism, cost, reliability; "One more thing to break".
- Very difficult to mount things (engines, missiles, control surface fairings) under the wings. (F-111 and Tornado managed to).
- Sweeping the wing without sliding the wing root forwards will move the center of lift aft. Horizontal stabilizers have to push down harder in order to balance the airplane, increasing their drag.

Forward-Swept Wings

e.g. Junkers 287, X-29, Su-47, HFB-320, Williams V-Jet 2, Rutan Boomerang, Saab Safari, Viking Cygnet, LET L-13, etc.

Advantages:
- Tendency of air to flow inwards overcomes some of the problems caused by spanwise flow: Wing roots want to stall before wingtips, preserving aileron control. Vortices are less intense; Slightly lower induced drag.
- Reduction in wave drag, like in aft-swept wings. But shockwaves form inboard first, preserving smooth flow around ailerons.
- Wing spar crosses fuselage aft of CG, thus helping to keep pilot, bomb bays, landing gear, etc., close to the CG.

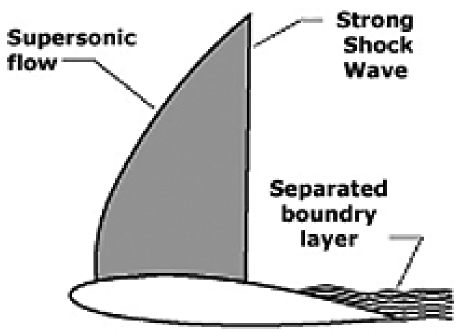
(The LET L-13, SAAB Safari, Malmo/Bolkow Junior, Schleicher ASK13, ARV Super 2, etc., have forward-swept wings so as to put the occupants close to the center of lift, minimizing the need for tail down-force and fuselage structural weight. The more conventional ways to accomplish this are high wings with the spar going through the fuselage overhead, or low wings with the spar going under the seat).

Disadvantages:
- Reduces yaw stability, i.e. requires bigger vertical stabilizer (or fly-by-wire). Prone to "reverse Dutch roll" dynamic mode.
- Because wing root has greater chord than wing tip, stall introduces a more severe pitch instability than in conventional (aft-swept) wings. Wing root stall causes center of lift to move forwards more, and faster, than aft-swept wing tip stall.
- Not any more agile/maneuverable than conventional wings. (USAF somewhat disappointed by X-29. Not exceptional).
- When wing generates lift, most of the lift is ahead of the fuselage attachment, twisting the wing upwards, increasing its angle of attack… generating more lift, twisting it more… generating more lift, twisting it more… This will either be stopped by (1) a nonlinearity in the lift as a function of alpha (i.e. the wing begins to stall), and/or by (2) a nonlinearity in the twist as a function of lift force (i.e. the wing becomes stiffer as it twists)… or (3) the wing will snap off.

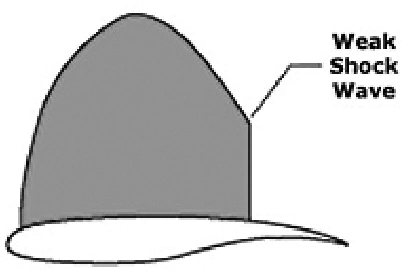
Only with modern advances in composite materials has it become possible to make fast (i.e. high subsonic speed) airplanes with wings that are stiff enough (and nonlinearly stiff, in a deliberate tailored way) to be forwards-swept without snapping off.

For more info: http://www.nasa.gov/connect/ebooks/sweeping_forward_detail.html , a NASA book about the X-29. Free PDF online.

Delaying the Onset of Wave Drag, 3: Supercritical Airfoils

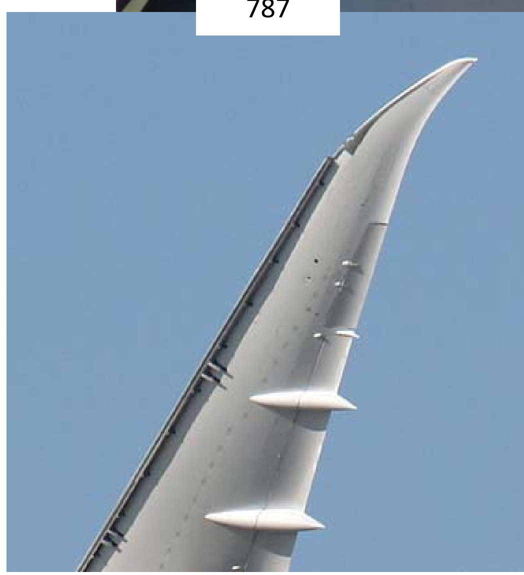


Conventional Airfoil
M = 0.69



Supercritical Airfoil
M = 0.80

787



A330

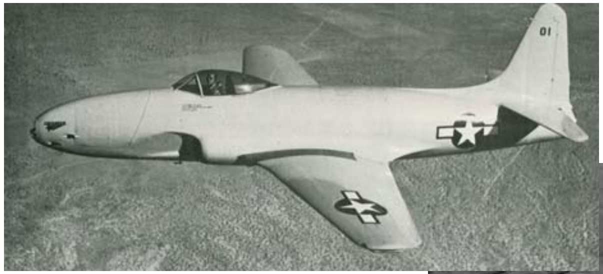
Delaying the Onset of Wave Drag, 3: Supercritical Airfoils

How can an airplane fly closer to the speed of sound without the air over the wing forming a shockwave?
How do we get Mcrit to be closer to M=1?

Supercritical airfoil:

- Move the “crest” (highest point) of the airfoil aft, and make the top flatter, so that the low-pressure region is distributed over most of the upper surface instead of being concentrated near the front.
- Lift is more “spread out”.
- Lowers the top speed of the air over the wing, delaying shockwaves.
- Makes it easier for the air to flown down over the back into higher-pressure regions, delaying/eliminating separation.
- 1960s research indicated these features would be advantageous in trans-sonic flight. Whitcomb at NASA (same guy as winglets and area rule!) brought it all together and got them to test this on an F-8 in 1971. Great results. Used in every airliner since.

Delaying the Onset of Wave Drag; In summary



Delaying the Onset of Wave Drag; In summary

In the end, some ***combination*** of…
(1) wing sweep
(2) supercritical airfoil curvature, and
(3) reduction in wing thickness
… can be used to raise Mcrit to above the desired cruise speed,
so that the airplane can cruise close to the speed of sound, without making shockwaves.

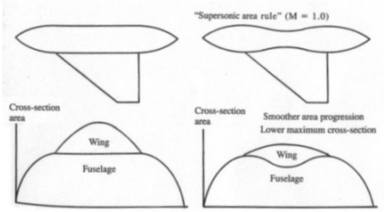
For example; The thin straight wing on the P-80 had an Mcrit around Mach 0.9, which for the time allowed for record high cruise speeds. However, those wings had relatively poor low-speed performance: They stalled abruptly and at high speeds, requiring lots of runway and a careful pilot. And because they were thin, they had to be structurally heavy. (More on this when we talk about structural "height"). Sweeping the wings, as they did on the F-86 and B-47, allowed the wings to still have an Mcrit of around Mach 0.9 while being a little thicker, making for better (but still not great) low-speed performance, and also for lighter structural weight. The introduction of the supercritical airfoil allowed wings of similar sweep (e.g. 777, A330) to still have an Mcrit of around Mach 0.9 while being quite thick, so they have good low-speed capabilities, a gradual and forgiving stall, don't need two miles of runway, and are structurally quite lightweight.

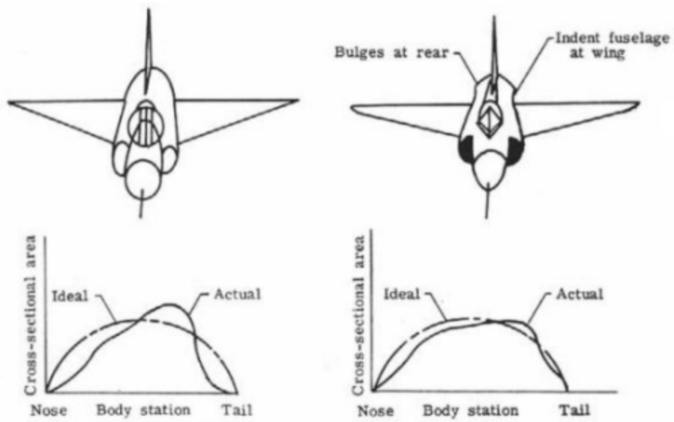
Shockwaves form because air speeds up over the tops of the wings, to make lift. A wing at a lower alpha, with a lower CL, will have a slightly faster Mcrit than that same wing at a higher alpha. This means…

One: The same airplane, when heavier (requiring more angle of attack), will start making shockwaves at a slightly slower speed. So the lighter the airplane, the faster it can cruise before making shockwaves. And

Two: The higher an airplane flies, the thinner the air gets. The wings then need to either fly faster, or fly at a higher alpha, or they'll generate less lift. If a wing starts making shockwaves at a certain combination of speed and angle of attack, then the lighter the airplane gets (e.g. as it burns fuel), then the higher the airplane can fly (and thus experience less drag) without exceeding that critical speed and angle of attack. (See slides 328-329 for more details on this).

Reducing Wave Drag





(a) YF-102A before area ruling. (b) F-102A after area ruling.

SEA HAWK

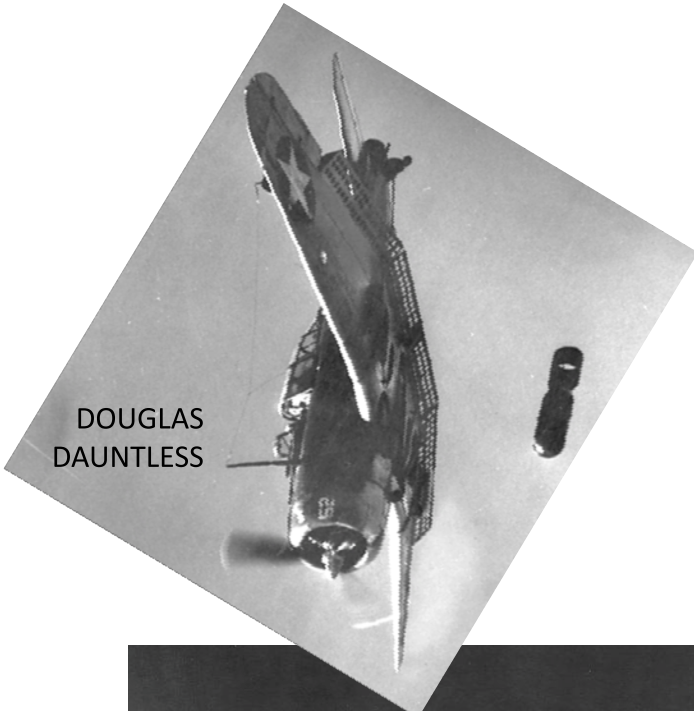
Reducing Wave Drag

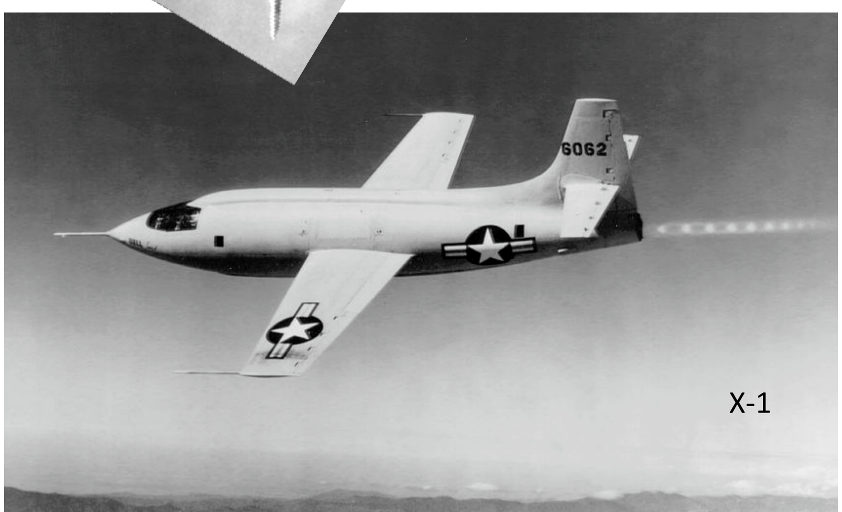
Say you do want to fly faster than sound. There will be shockwaves everywhere, no way to avoid it. But how to minimize wave drag?

Compressibility drag can be minimized if the changes in airplane cross-section are not abrupt. This means:

- **Pointy noses**
- **Thin wings**
- **Long, slender fuselages** (high "fineness ratio")
- **Whitcomb's "Area rule":**
  - A reduction in fuselage cross-section ("waist", "Coke bottle fuselage") where the wings are,
  - Some enlarged canoe fairings ("shock bodies") around the wing trailing edges,
  - A bulbous fairing sticking out the leading edge of where a T-tail's stabilizers intersect

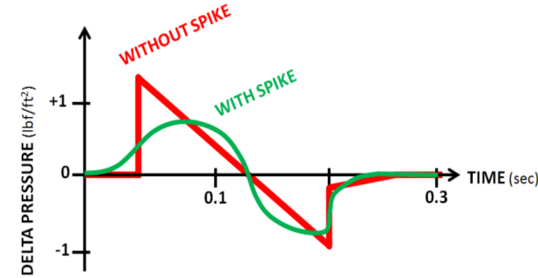
The "Sound Barrier"; A bit of history



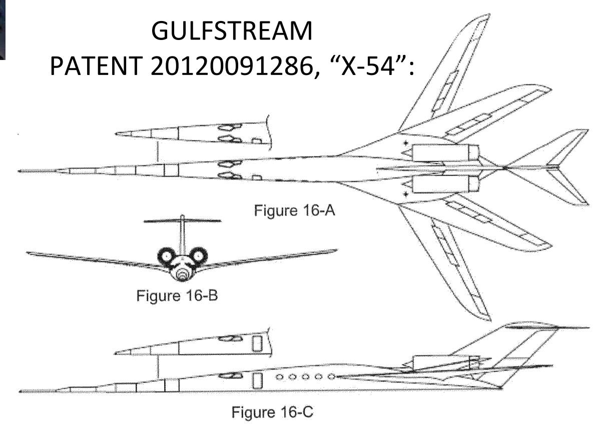


- During WW2, it was noticed that even airplanes with greatly increased thrust (such as twin-engine fighters, early jets, and even rocket-powered aircraft like the Me-163) could not fly much faster than 600 mph, even in a dive. Drag seemed to increase immensely at those speeds.
  - We now know that this is due to shockwaves, that their onset can be delayed by various features such as swept wings and thin airfoils, and that their intensity at and beyond the speed of sound can be reduced by more gradual changes in cross-sectional area.
- It was also noticed that the controls would vibrate and lose effectiveness.
  - We now know that this is because a shockwave will often separate the flow aft of it, causing the control surfaces to sit inside a sheet of turbulent low-density air.
- It was also noticed that some airplanes would sometimes come apart in the air at these speeds.
  - We now know that this is because of the aforementioned vibrations, because of aeroelastic effects such as flutter (More about this when we discuss structures), and because supersonic flow sometimes concentrates intense pressures over relatively small areas. In short: Supersonic airplanes must be stiffer than subsonic airplanes.
- It was also noticed that dive-bombers, and other airplanes that attempted high speeds, would sometimes get stuck in dives and be unable to pull out. Speeds of ~600mph would cause a strong nose-down moment, now called “Mach tuck”. (Dive bombers eventually included large air brakes to prevent dangerous speeds). Test pilots learned that, if nose-up commands stopped working at high speeds, the airplane should be slowed down immediately by any means such as cutting the power and even deploying the gear. Several test-pilots died in dives before this was learned.
  - We now know his is because, as shockwaves form and the flow around wings becomes supersonic, the center of lift moves aft. Very high elevator forces are needed to make it through the sound barrier in horizontal flight. Nearly all supersonic airplanes have stabilators (i.e. all-moving horizontal tails, a.k.a. “all-flying tails”), starting with the X-1. In a way, elevators were enlarged until they took up the entire horizontal stabilizer.

Supersonic transports; Ever again?



GULFSTREAM
PATENT 20120091286, “X-54”:



The Concorde was flown commercially for decades. The Tu-144 did some commercial flying. The Boeing "2707" SST was never completed.
Why did supersonic transports never take off? Why are we back to subsonic-only travel?

• Supersonic travel means more drag, and much more fuel per passenger per mile. Few people could afford this premium (let alone want to).
The market is too small. The development costs of a supersonic airliner would not pay for themselves in sales.
(In fact, it's debatable whether Concorde operations were ever profitable or done mostly for the prestige / brand value).

• Most of the people who used to travel by Concorde (the "1%") now fly in business jets. More convenience, often shorter door-to-door time (flying at smaller airports) despite more time in the air than if the airplane were supersonic. More comfort too. (Concorde seats are small!)

• Gulfstream, and other companies such as Aerion (SBJ & AS2), Boom (XB-1), and Spike, have recently talked about developing small supersonic transports.

• NASA has been working with Gulfstream and Boeing, and more recently Lockheed (QueSST), to research technologies to

reduce the sonic boom so that a small SST could be allowed to fly over land in the US.

• There is also research into supersonic-optimized engines, inlets, wings, etc. Even Boeing occasionally does studies into the feasibility of a small SST, looking at what the market might be, what technologies would be needed, and how far along they are:

  • Short news article: http://www.nasa.gov/aero/centers_tackle_sonic_boom.html
  • Only accessible within Boeing (but presented publicly once): Slides with images from SST tests and analyses by NASA, UW, Boeing, and other companies. Shows latest progress about… optimal inlet and nozzle shapes for each speed, various wing/tail/canard configurations, nose shapes and engine locations to minimize boom intensity and engine noise, estimates of fuel burn per passenger, range, market (sales) potential… http://a.web.boeing.com/BoeingSupersonics
  • Boeing 765 report: Market (ideal size & range), fuel burn per passenger, noise reduction, engine size/location/bypass ratio/secondary flow, fuselage/wing shape impact on drag and boom, best altitude, cockpit visibility, structures, CG envelope, tail or no tail… https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100030607.pdf

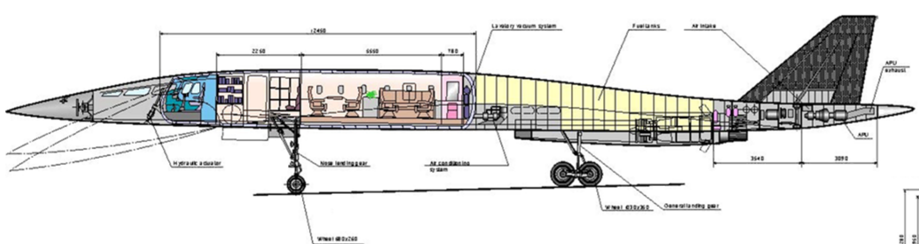
• See Gulfstream patents 428381, 8448893B2, 8789789, 20120043429A1, and 20120091286, look up the X-54 project, and/or check out Gulfstream's presentation to the FAA: https://www.faa.gov/about/office_org/headquarters_offices/apl/noise_emissions/supersonic_aircraft_noise/media/BaltimorePublicMeeting-Gulfstream.pdf

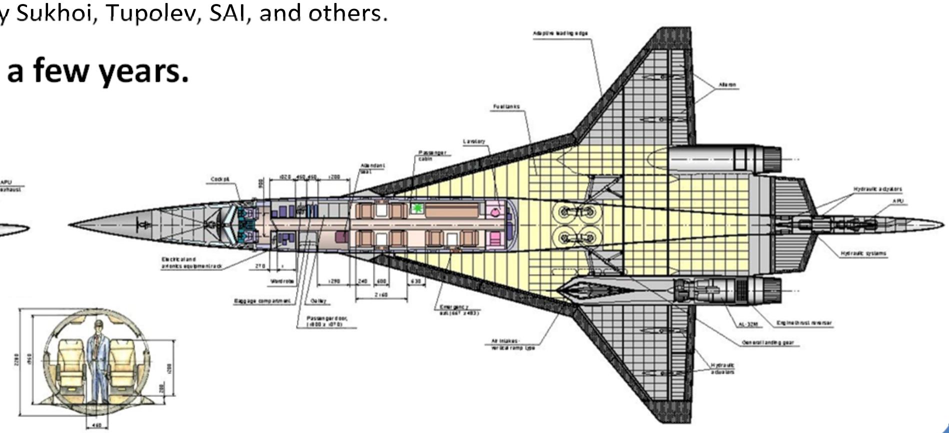
• Aerion: http://aviationweek.com/nbaa-2015/flexjet-order-20-supersonic-jets-boosts-aerion , http://fortune.com/2015/11/24/supersonic-private-jet/ , http://www.bloomberg.com/bw/articles/2014-11-13/aerion-as2-supersonic-business-jet-could-fly-by-2019

• Lockheed QueSST: http://www.lockheedmartin.com/us/products/QueSST0.html , https://www.nasa.gov/press-release/nasa-wind-tunnel-tests-lockheed-martin-s-x-plane-design-for-a-quieter-supersonic-jet

• A *Google search for* "supersonic business jet" will reveal additional studies by Sukhoi, Tupolev, SAI, and others.

Bottom line: **A supersonic bizjet might become reality in a few years.**





TUPOLEV 444

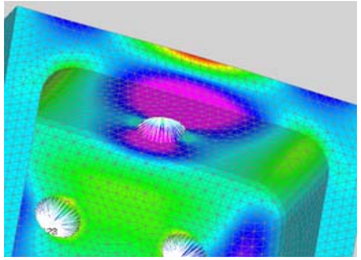
Structures

Airplane Structures Terms

To start our introduction to the basics of aeronautical structures engineering, here are some terms worth defining:

- A **load** is a force such as an object's weight, the aerodynamic pressure over a tail fin, the pull of the engine on its mounts, etc.
- **Stress** is force per cross-sectional area. If a 500-pound weight hangs by a rope that has a cross-section of one square inch, then this weight causes the rope to experience a tensile stress of 500 pounds per square inch. If the rope has knots or other discontinuities, the stress there will be higher. The average compressive stress on the soles of your shoes is your weight divided by the soles' total surface area. In some places the stress will be higher than this average (e.g. under your heels), in other places the stress will be lower.
- The **strength** of some structural *component* is how much load it can take before "failing". (The **strength** of some *material* is how much stress it can take before "failing"). **Failure** can be defined differently in different situations: Yielding [i.e. deforming permanently], breaking apart, buckling, etc.

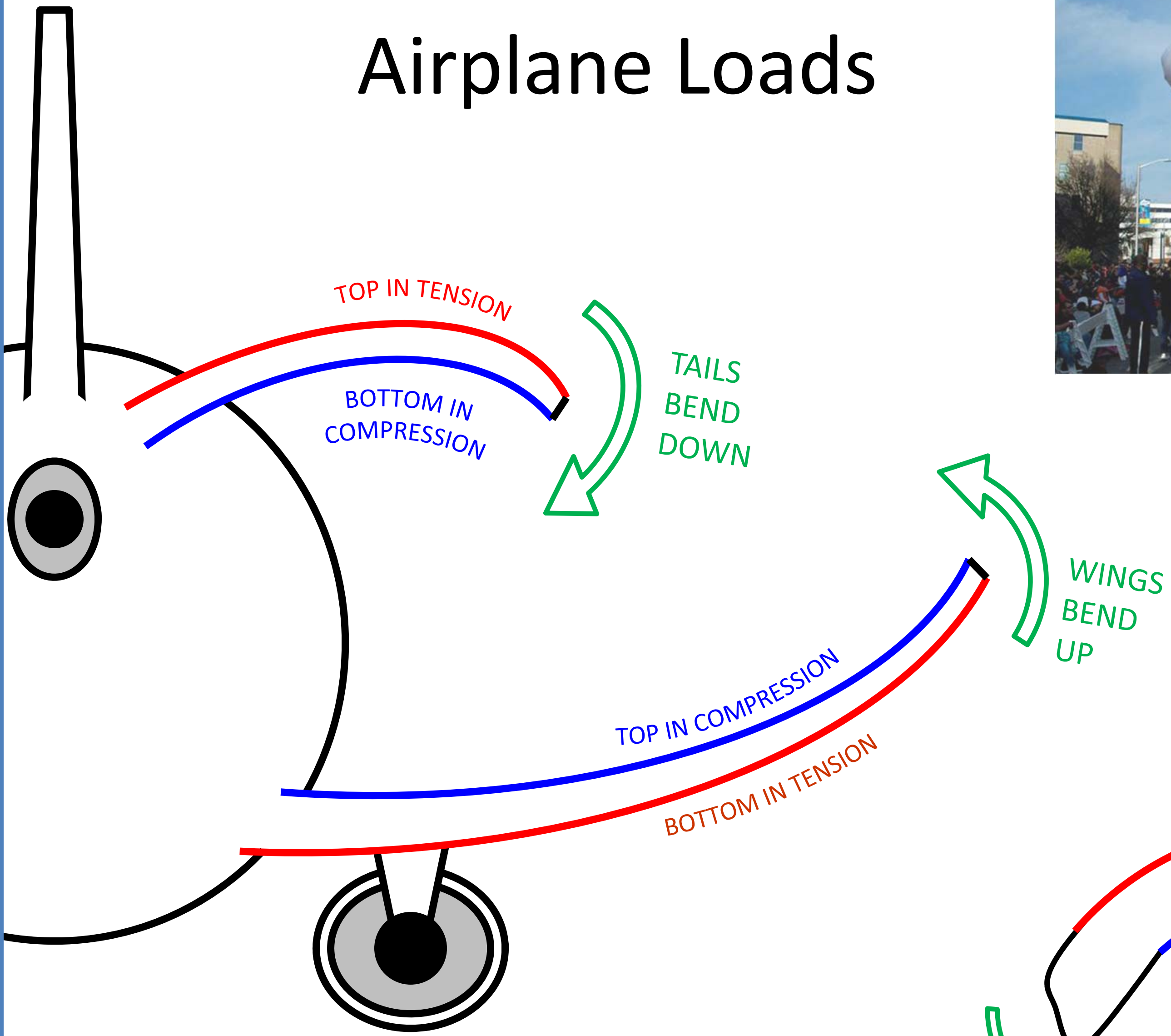
  (A material starts to break when a spot on it exceeds a certain stress. Therefore, most structures engineering has to do with figuring out the stress at every spot of a proposed structure when that structure experiences the maximum load that it must survive during the life of the airplane. If the stress at some spot exceeds the strength of the material, then that part must be thickened in order to reduce the stress by increasing the cross-sectional area, or a stronger material must be used, or the shape must be changed to one that has less-intense stress concentrations. Therefore, most structures engineers do stress analysis, or simply, "stress").
- **Strain** means a deformation, i.e. a change in shape, e.g. bending or stretching, caused by a load.
- **Stiffness** is how easy or hard it is to deform (strain) something as a function of the stress on it. A *component* is relatively stiff if it can take a lot of load and only deforms a little. A *material* is relatively stiff if it can take a lot of stress and only strains a little. (A plastic bag is less stiff than a paper bag – it deforms more, even with the slightest force… However, it is often stronger than a paper bag – i.e. it can carry more weight before it rips).



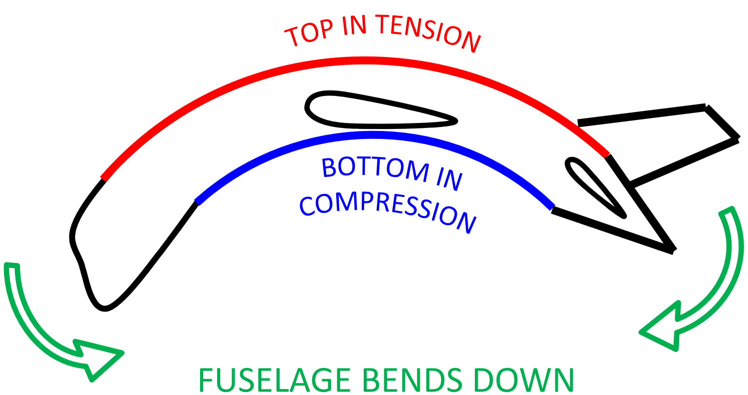
A finite element model that represents different ranges of stress by different colors.

- **Toughness** and **robustness** have to do with how much of the strength is lost when there is some damage. A tough material / A robust structure can take quite a bit of damage while still maintaining the strength that it is required to have in order to keep holding the airplane together.
- **Durability** has to do with how many times something can be used before it loses too much of its strength. This does not necessarily mean that the material is being abused, just normal everyday use.

Airplane Loads



FUSELAGE PRESSURIZED, EXPANDS LIKE A BALLOON, SKIN & STIFFENERS IN TENSION



FUSELAGE BENDS DOWN

Airplane Loads

- During flight, the **wings are bent up by lift**. So the lower wing components are in tension and the upper wing components are in compression.
  The horizontal stabilizers are small upside-down wings, so they see the same loads but in reverse: tops in tension, bottoms in compression
- Similarly, **the fuselage is bent down under its own weight** like the hollow and cylindrical cantilever beam that it is. So the top of the fuselage is in tension and the bottom may be in longitudinal compression.
- “May be” because **the airplane is pressurized**,
  adding tension to all of the skin, like a balloon.
- There are other things too: The engines pull against their mounts,
  the landing gear gets slammed at the end of every flight,
  seat structure must survive a crash…
  But the “main” loads used to size most structure come from
  lift and pressurization.
- Or maybe this is just my bias showing, as someone who works with airplane fatigue. These fuselage pressurization, fuselage bending, wing bending, and tail-fin-bending loads are the ones that induce stresses that cause fatigue. The stresses from the engine thrust, from the landing gear, etc., can be just as intense, but for various reasons, they rarely result in fatigue cracking.

Materials

- How to minimize weight while having the required strength and stiffness?
- A quick thought-experiment:

	(from Google)		How much material would be required to take a 20,000-pound load? (Assuming we need a one-foot-long cylindrical rod)			
	Density	Tensile Strength	Required Cross-Sectional Area (20,000 lbs divided by tensile strength)	Required Diameter (Area of a circle is πr^2; so diameter is $2*\sqrt{(A/\pi)}$)	Volume (twelve-inch length times cross-sectional area)	**Weight** (volume times density)
Steel 4330+V	0.28300 lbs / in^3	188000 psi	0.106 in^2	0.37 in	1.28 in^3	**0.361 lbs**
Aluminum 7086	0.09750 lbs / in^3	99000 psi	0.202 in^2	0.51 in	2.42 in^3	**0.236 lbs**
Fiberglass (45% E-Glass, Polyester resin)	0.05780 lbs / in^3	36300 psi	0.551 in^2	0.84 in	6.61 in^3	**0.382 lbs**
"Styrofoam" (expanded polystyrene foam)	0.00087 lbs / in^3	51 psi	392.157 in^2	22.35 in	4705.88 in^3	**4.094 lbs**

Materials

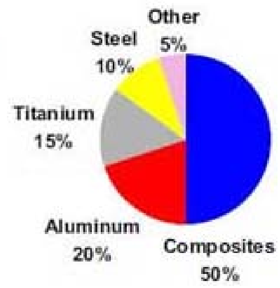
How to minimize weight while having the required strength and stiffness? Use materials that have the ***highest strength-to-weight ratio***. Not just light, not just strong, but both. Especially when it comes to structure that is in tension, the material properties (as opposed to the shape) play a huge role:

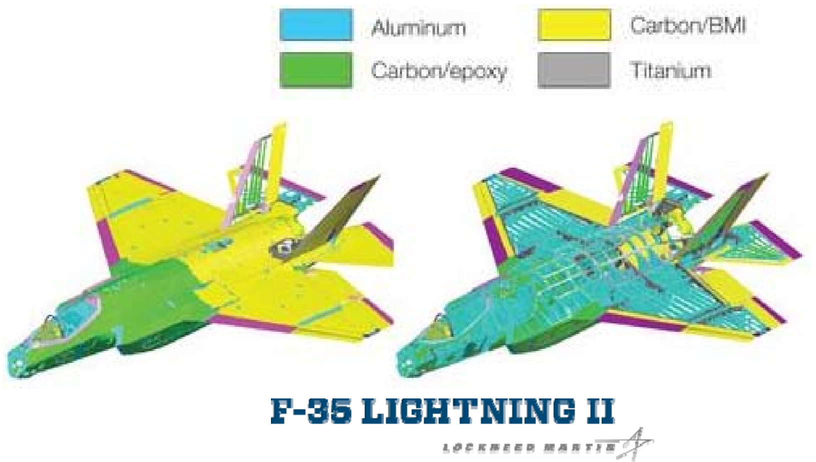
- Say that we have to make a cylindrical rod, one foot long, that experiences tension loads.
- Say that the rod needs to NOT fail when it takes loads of up to 20,000 lbs.
- Say that the rod could be made of Steel 4330+V, or of Aluminum 7068, or of Fiberglass (45% E-Glass in Polyester resin) or of Styrofoam. (I picked these materials because their properties were easy to look up with Google).
- For each of these materials:
  - **How wide would the rod be in order for the stress to be below the material's tensile strength?**
  - **How much would that rod weigh?**

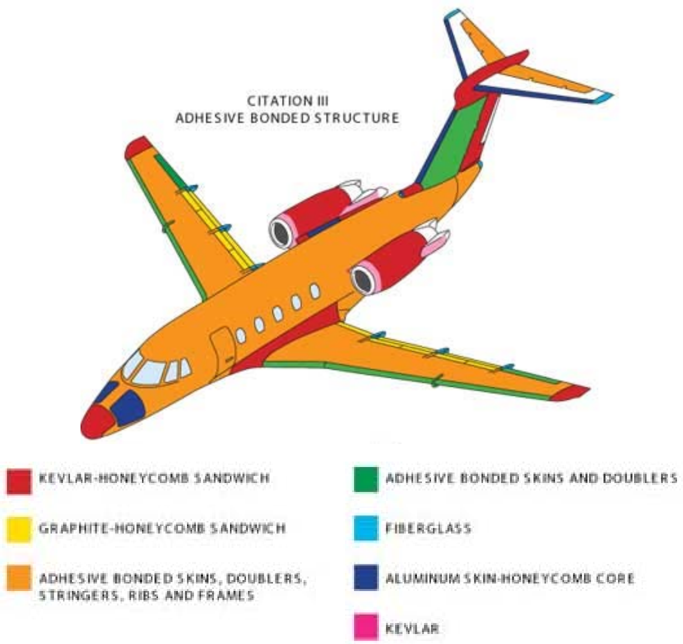
  (If you take a structures or statics or strength-of-materials class, the first homework will probably look something like this).
- Do the math… and the aluminum would be the lightest. A one-foot rod capable of taking one ton of tension would weigh about one third of one ounce. It would be over half an ounce if it were made of steel, and even more if it were fiberglass. If it were foam, it would need to weigh six ounces… Over ten times as much! (That's because foam's compressive capabilities are much better than its tensile capabilities, while other materials don't have as large a difference in that regard).
- Bottom line: **Out of the materials we chose, to take a certain load, aluminum would be the lightest**. (Carbon fiber would be even better). Steel can take twice the load per square inch, but it's 3x as heavy per square inch. Replace an aluminum component by a steel component, and you get a component that is 50% thinner but that weighs 50% more.
- Note that this example assumes perfect material. Material with flaws – or even with tapers, fastener holes, and other features – would have less tensile strength than the numbers shown here. This is taken into account during structural analysis.
- Airplane structure has **margins of safety**. This is in case of imperfect data about material properties (e.g. mistakes made during testing), in case a batch of material and/or of components is made incorrectly, in case nearby structure is damaged or breaks, in case estimates about airplane weight or wind gusts were off, etc. Certain margins are required (e.g. structure is made strong enough to take all the loads it would experience in case each nearby component breaks; ***fail-safe loads***), some are added by manufacturers to make structure more ***repairable*** (e.g. up to 1/3 of the thickness of many skins can be ground off to get rid of corrosion), etc.

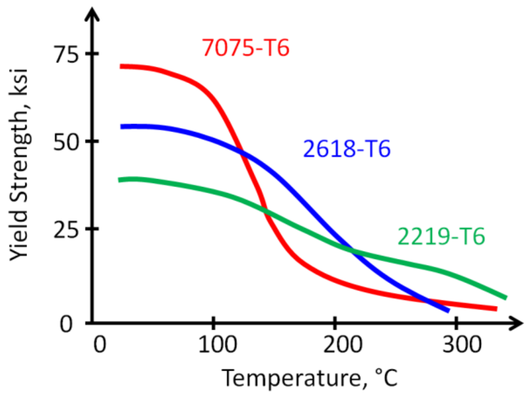
Materials

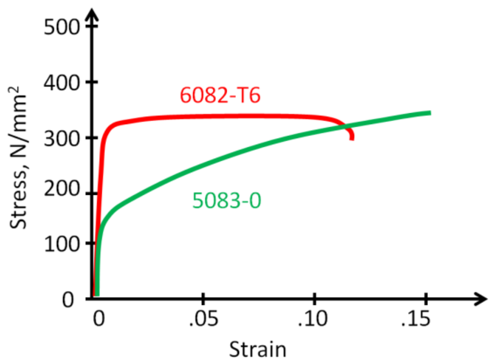

787 DREAMLINER
Carbon laminate
Carbon sandwich
Fiberglass
Aluminum
Aluminum/steel/titanium pylons


Other 5%
Steel 10%
Titanium 15%
Aluminum 20%
Composites 50%


Aluminum
Carbon/BMI
Carbon/epoxy
Titanium
F-35 LIGHTNING II
LOCKHEED MARTIN


CITATION III
ADHESIVE BONDED STRUCTURE
KEVLAR-HONEYCOMB SANDWICH
GRAPHITE-HONEYCOMB SANDWICH
ADHESIVE BONDED SKINS, DOUBLERS, STRINGERS, RIBS AND FRAMES
ADHESIVE BONDED SKINS AND DOUBLERS
FIBERGLASS
ALUMINUM SKIN-HONEYCOMB CORE
KEVLAR

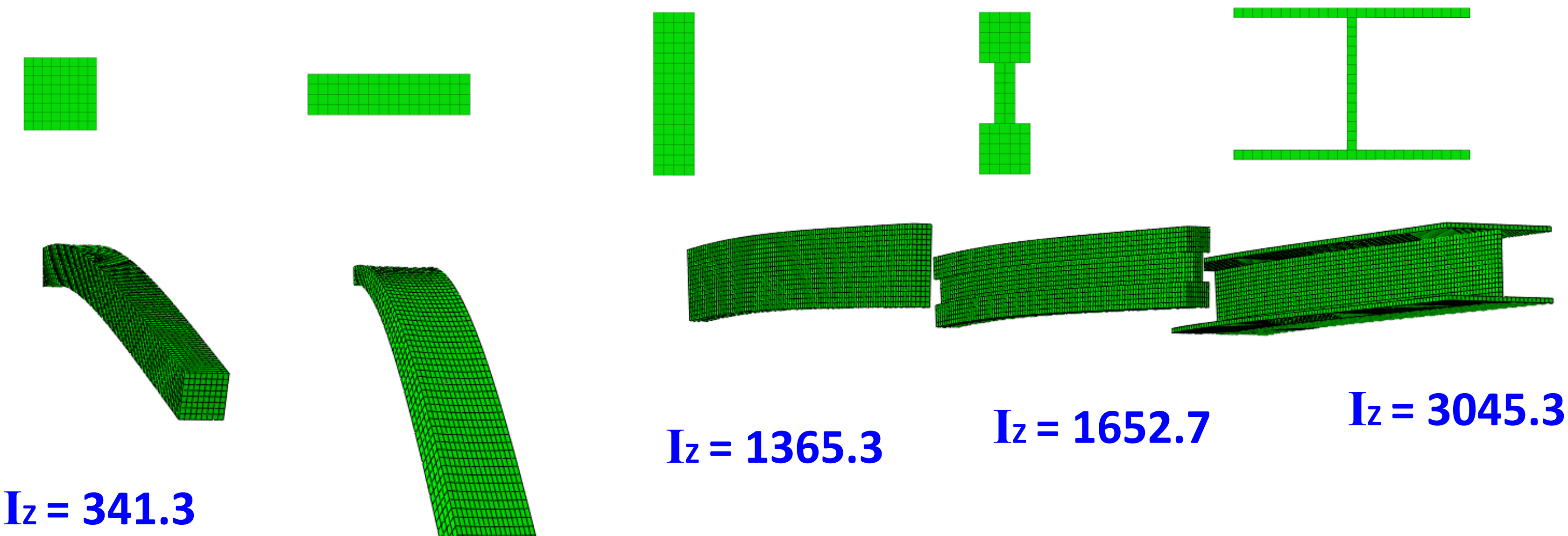

Yield Strength, ksi
75
50
25
0
0
100
200
300
Temperature, °C
7075-T6
2618-T6
2219-T6

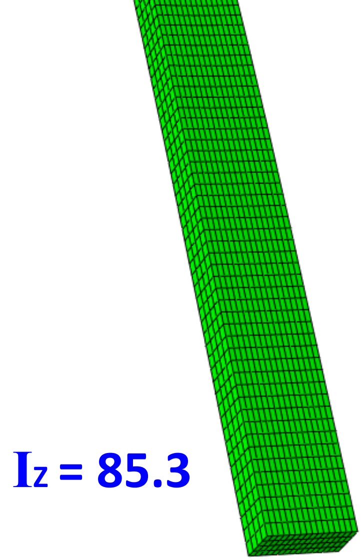

Stress, N/mm²
500
400
300
200
100
0
0
.05
.10
.15
Strain
6082-T6
5083-0

Materials

- Does this mean aluminum is the best aerospace material? Almost. **Carbon fiber and titanium are often even better, but are more expensive and more difficult to manufacture**. Carbon fiber is worth it when weight must be minimized at any cost. Titanium is worth it for certain high-temperature applications, and when CFRP structure needs metal components attached to it (e.g. stiffeners, brackets). That's because the coefficients of thermal expansion of CFRP and Ti are low, but aluminum's is high. If you make something out of some CFRP parts and some AL parts, and then heat or cool the assembly (such as by flying high, or by running an engine nearby), the expansion or contraction of the AL will stress it and the CFRP it's attached to, while the Ti would not, because Ti does not expand or contract as much.
- Very high temperatures may require steel. Other metals lose too much strength at high temperatures. For the X-15, even that was not enough, so the whole airplane was made of inconel, a nickel alloy used to make engine parts. The Shuttle belly is made of ceramic tiles to take the heat of re-entry!
- To **minimize the cost and the amount of work** involved in building an airplane, many hobbyist airplane builders use steel or fiberglass instead of aluminum or carbon fiber: They sculpt their airplane out of foam and cover it with fiberglass, or make it out of welded steel tube covered in fabric. The structural weight ends up higher, but the airplane is finished in a few months rather than in a few years.
- Different alloys of aluminum (and steel, and Ti) have different relationships between weight, strength, durability, cost, and ease of manufacturability. So **each part of an airplane may end up being made of a slightly different material** that is optimal for that particular shape (which must be manufactured), location (which may or may not be easy to access for maintenance), local stresses and temperatures, exposure to water or oil or fuel or chemicals, etc.
- Many handbooks collect information about different materials to help designers choose the optimal ones for each component of their airplanes. For example, here are stress-strain curves for two different kinds of aluminum at room temperature: 6082-T6 is stronger (can take more stress), but 5083-0 is more flexible (can take more strain). At higher temperatures, things change: 7075-T6 is stronger than 2618-T6 or 2219-T6 at room temperature, but becomes the weakest of the three once temperatures exceed 150°. Aluminum 2219, the weakest at room temperature, becomes the strongest past about 220°.

What shape is best at resisting bending?



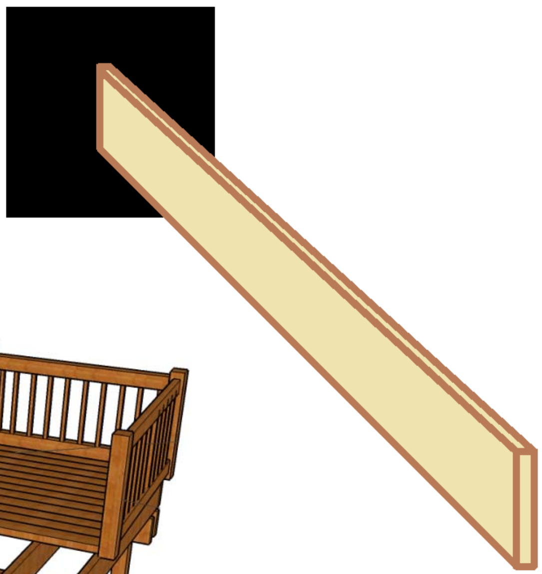


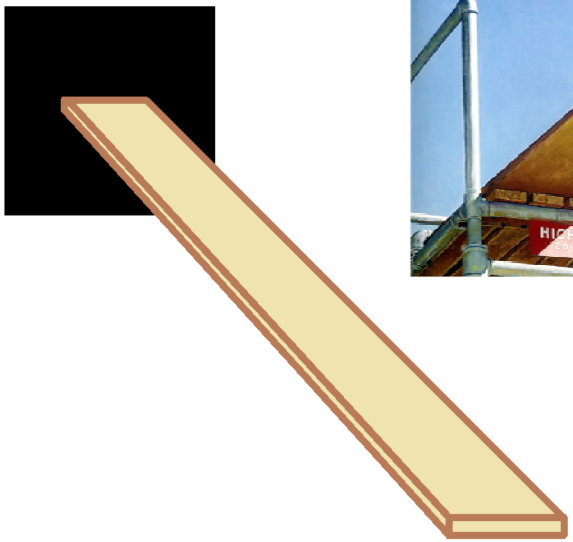
These five beams are all reacting (i.e. holding up against) the same downwards force.

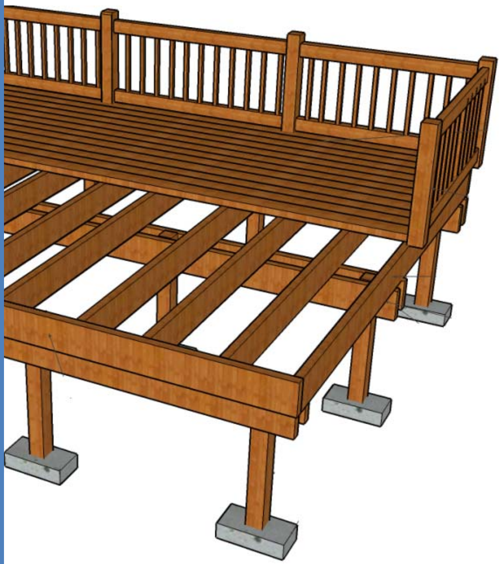
What shape is best at resisting bending?

- We have only talked about the weight-efficiency of ***materials***. But what ***shapes*** are most weight-efficient? Given a certain amount of a certain material, what shape maximizes stiffness and weight?
- When it comes to bending, the key to stiffness is the "moment of inertia". To make a long story short: The contribution of each bit of material to the component's moment of inertia depends on the ***CUBE*** of how far up or down that bit of material is. (A famous formula among structures folks is "**$bh^3/12$**").
- For example, take a beam with a solid square cross-section, 8 units by 8 units, i.e. 64 square units of material. (One "unit", is, let's say, 1/8 of an inch). The moment of inertia will be **341.3** ($8 \times 8^3/12$).
- If we "flatten" this beam into a board that is 4 units deep and 16 units wide, the moment of inertia drops to **85.3** ($16 \times 4^3/12$). Much easier to bend up or down. It's like a diving board.
- If we squeeze that beam into a taller beam that is 4 wide and 16 tall (or just rotate that board), the moment of inertia goes up to **1365.3** ($4 \times 16^3/12$). Much harder to bend in the up-down direction.
- (For example, a ruler is very floppy and easy to bend in one direction, but very rigid and hard to bend in the direction at 90 degrees to it).
- If the contribution from each piece of material depends on how far up or down it is… then put all the material along the top and bottom! Keeping the same height (16), what if we have some material along the top in a 5x5 square, and some along the bottom in another 5x5 square (these squares are known as "beam chords"), and then a thin vertical "web" (just two units thick) connecting them? The moment of inertia is now **1652.7**! (And, it has 62 square units, not 64. Close enough).
- The extreme: a sixteen-unit-tall, one-unit-thick vertical web, with all the rest of the material along the very top or very bottom in thin chords ("flanges"), four of them that are one unit thick and 12 units wide. The moment of inertia is now **3045.3**! It's almost ***TEN TIMES*** as stiff as the original "square" beam, with the same amount of material! (So you make these beams as thin as you can, to get the most out of the material… except, at some thickness, it will buckle when loaded [like a soda can being stepped on], so it must be just a bit thicker than that).

The Importance of Structural Depth / Thickness





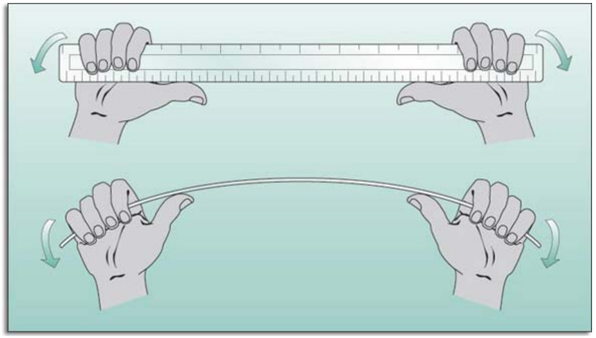


The Importance of Structural Depth / Thickness

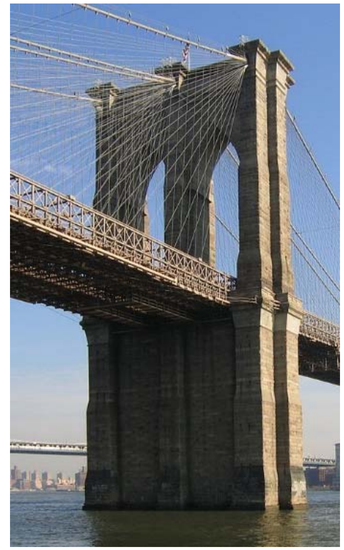
- The importance of beam "height" should now be clear. Material that is twice as far from the centerline of the component contributes eight times more to its stiffness!
- That answers questions such as: Why use stiffened panels? How can biplane wings be so lightweight? When wings are thin, why must they be so heavy? Why can "taller" / "deeper" structures be lighter?
- In case the answer to those questions is not clear: Here are two thought experiments illustrate why beam height is so important.
- (1) Compare a floor beam (e.g. under a wooden deck, or inside a house) with a diving board. Same piece of wood, but it is much stronger and stiffer – can support much more weight – when it is oriented so that it is vertically "deeper".

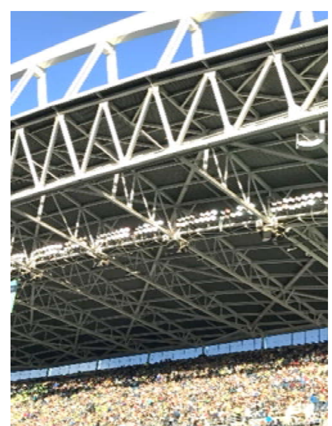
(And yes, the diving board is supported at one end while the floor beam is supported at both ends, but that doesn't make as big a difference).

- The classic illustration of this principle: A ruler is very easy to bend in one direction, but much harder to bend (much stiffer) in the other direction:

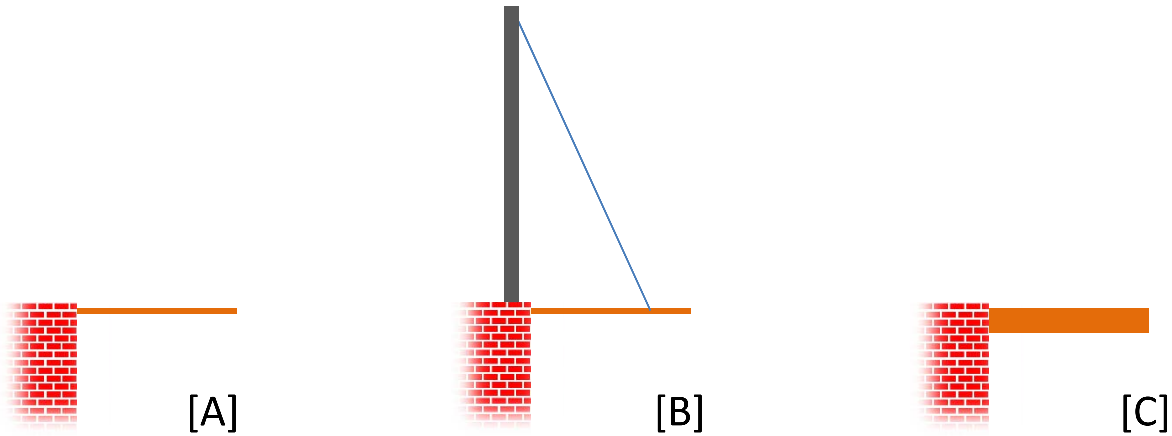


Trusses and Wires





- So now we understand what structures have to do, and we understand that it's easier if they have lots of "height" or "depth". In practice, what structural "architecture" / features can accomplish this?
- One traditional way to engineer a structure that is stiff (e.g. lots of "height") and strong, but lightweight, is a **truss**. A truss has one beam along the top (or along one side), another beam along the bottom (or along the other side), and diagonal beams holding them a certain distance apart. Think of the Eiffel tower, a crane, or a truss bridge.
- Another easy way to make stiff and strong structure with minimal materials is to use **external supports** like wires, e.g. a circus tent, or a radio tower, or a cable-stayed bridge.
- (Thought-experiment: A diving board [A] would be much stiffer and stronger if there were a pole sticking up from its base, and a cable connecting the top of the pole to the tip or even to the middle of the diving board [B]. The taller the pole, the more vertical – and more effective – the cable will be. Now, to be that strong and stiff without the pole and cable [i.e. as a "cantilever"], the board would have to be much thicker and heavier [C]).



Trusses, Wires, and Struts

CURTISS
JENNY

BOEING 247

CESSNA 182

PITTS 12

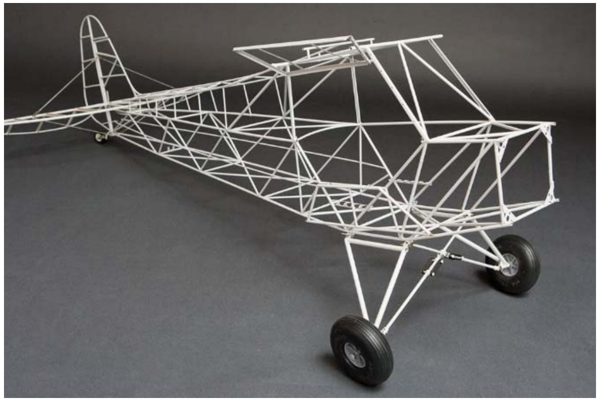
- These principles were applied to early aircraft, ranging from balloons and dirigibles to the Hawker Hurricane fighter of World War 2, and still today in some modern piston-powered planes e.g. the Pitts aerobatic airplane and the Carbon Cub bushplane.
- The strut under a Cessna's wings, and the wires between a biplane's wings, allow these wings to be much lighter, while still retaining strength and stiffness. When these external supports are used, the "height" of the beam is not the thickness of the wing; It's the height of the entire fuselage! (or even more than that, for airplanes that have "parasol" wings above the top of the fuselage).
- For slow airplanes, the low dynamic pressure and high induced drag means that the use of external struts and wires is worthwhile: They allow for much lower weight (of the wing and horizontal stabilizer structure) for only a little extra viscous drag and pressure drag. Bus above 150 mph or so, the added viscous drag and pressure drag from any external supports is no longer canceled out by the lower weight (lower induced drag), so at those faster speeds, ***cantilever wings*** (with no external supports) become worthwhile, despite their higher weight.

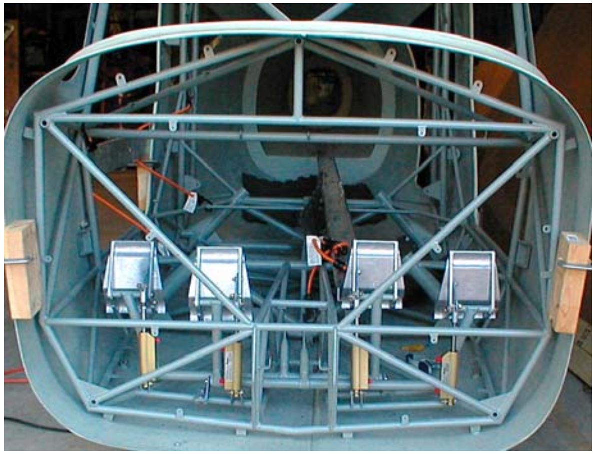
Welded Tubes

GLASAIR SPORTSMAN

SONERAI

PIPER CUB

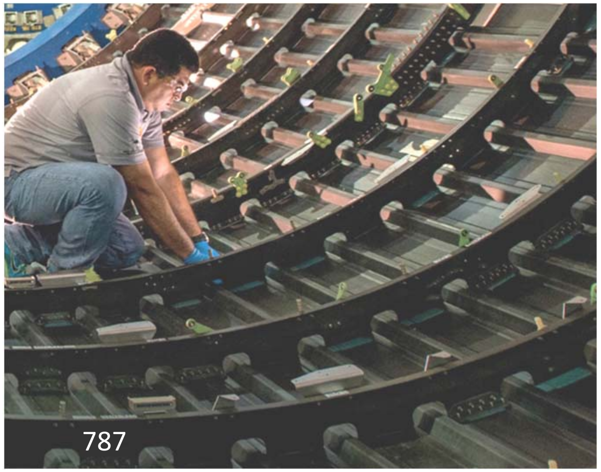




RV-12
ENGINE
MOUNT

Welded Tubes

- Another simple way to get a lot of height with relatively little material is to use a tube.
- Welded steel tube structure is cheap, relatively lightweight, and relatively easy to design and build.
- Many homebuilt airplanes and some racing airplanes still use welded-tube structure. Most piston-powered airplanes use welded-tube structure in their engine mounts.



787

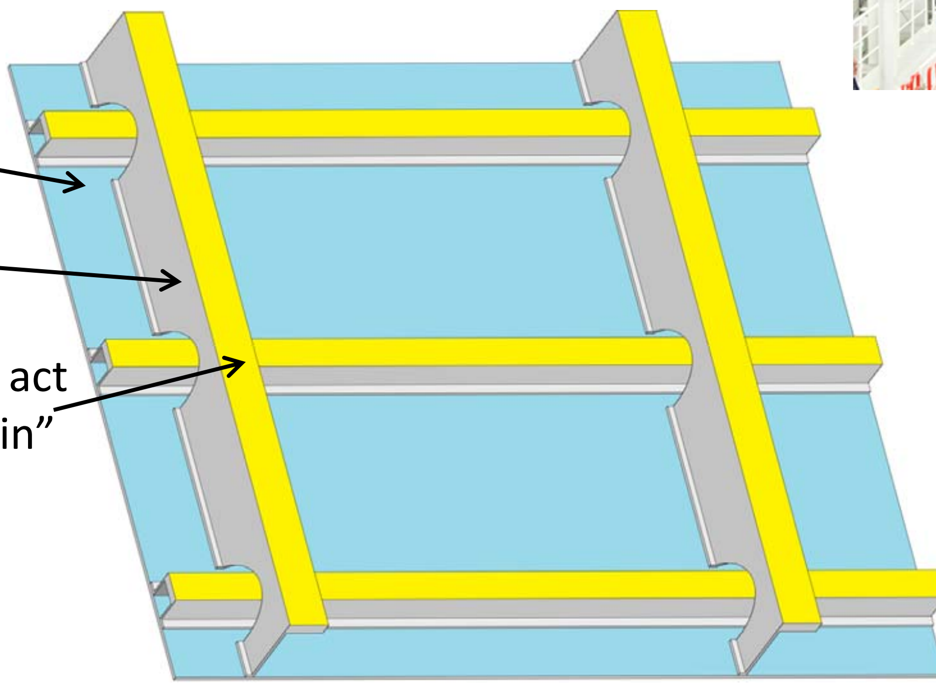
Stiffened Panels

A350

Outer skin

Stiffener web

Stiffener chords act like an “inner skin”

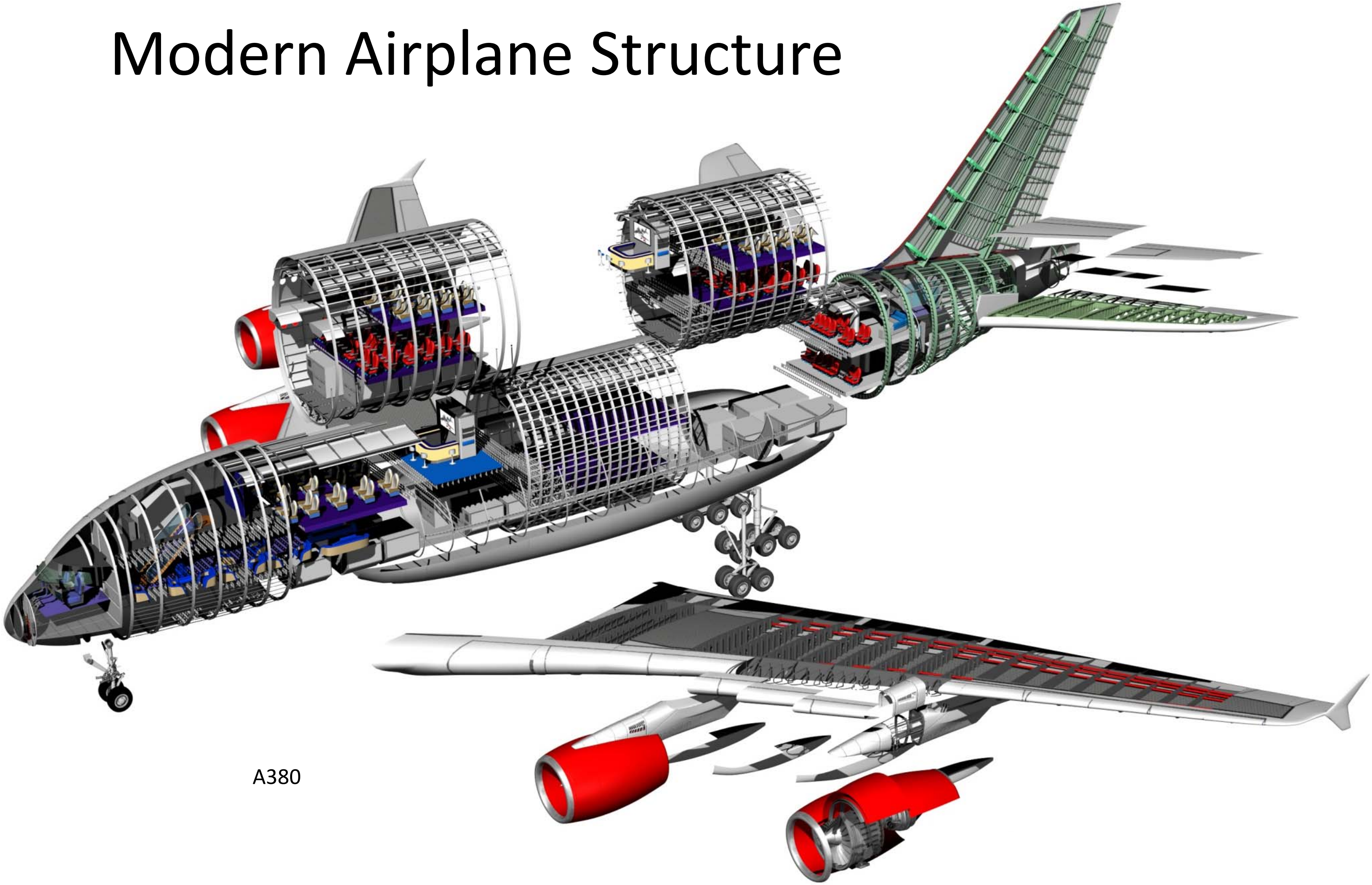


2707 SST

Stiffened Panels

- A metal sheet can be very easily bent or buckled. Two sheets glued together can still be bent or buckled fairly easily. But hold those two sheets apart – even if one sheet has lots of holes, and is held to the other sheet only by very thin metal connections – and the whole thing gets much stiffer, because the "height" or "depth" is much higher.
- Hence, we have ***stiffened panels***, where very thin lightweight beam "webs" hold a series of beam "chords" (which act like an inner skin) one to four inches away from the airplane's skin. **Most modern airplane structure (e.g. wings, fuselage, tail fins) is made up of stiffened panels.** The stiffeners (and, of course, the skins) can be made from bent sheet metal, which can be relatively thin (i.e. lightweight) and inexpensive.
- The images on the previous slide show "hat" stringers ("⎽⎾⏋⎿⎽") and "Z" frames. Frames and ribs and spars are typically Z or C channels and sometimes I beams. Stringers and longerons are typically hats or inverted hats ("⏋⎿⏌⎾") but are also sometimes shaped like "Z"s, "C"s, "L"s, or "I"s. The beam chords – which act like "inner skins" – are highlighted in yellow. The outer skin is blue. They maximize the resistance to bending by placing as much material as possible at a greater "height", making the skin much "taller" or "thicker".
- Stiffened panels make it possible for us to have ***monocoque*** fuselages (i.e. hollow, supported only by their outer structure, like an egg shell, no truss inside) and ***cantilever*** wings (i.e. not externally supported by wires or struts like Cessnas or old biplanes).

A Tour of Modern Airplane Structure

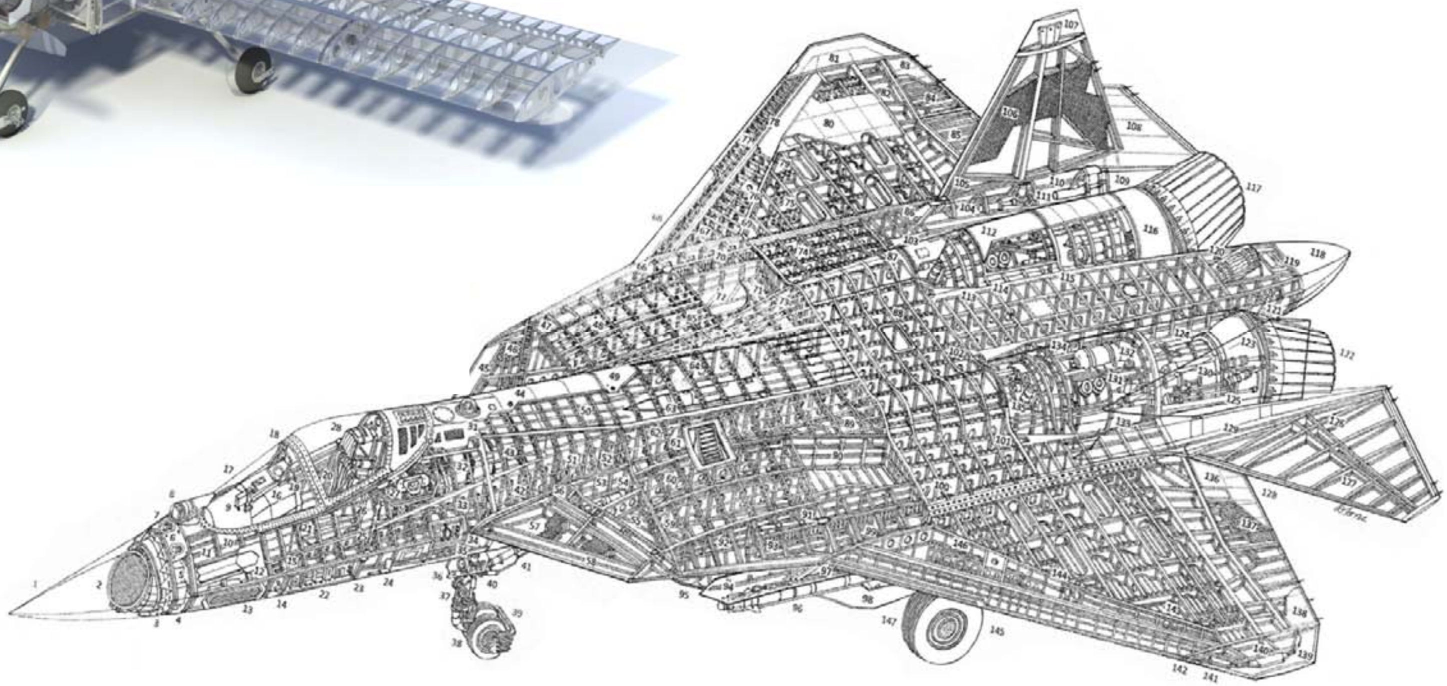


A380

A Tour of Modern Airplane Structure

RV-14

SUKHOI T-50 PAK-FA



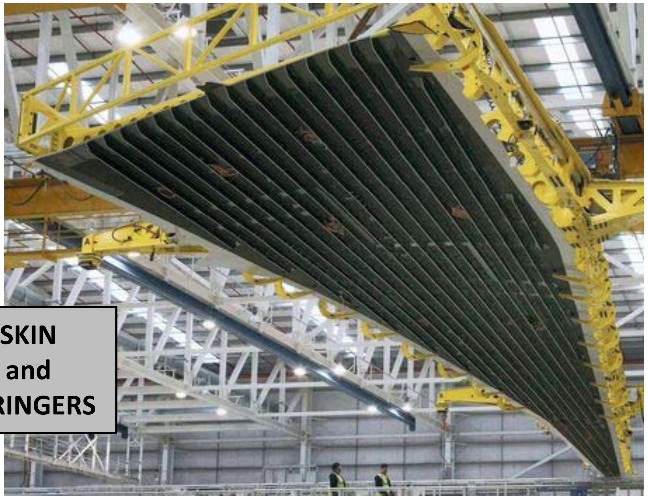
A Tour of Modern Airplane Structure

STRINGERS a.k.a. LONGERONS

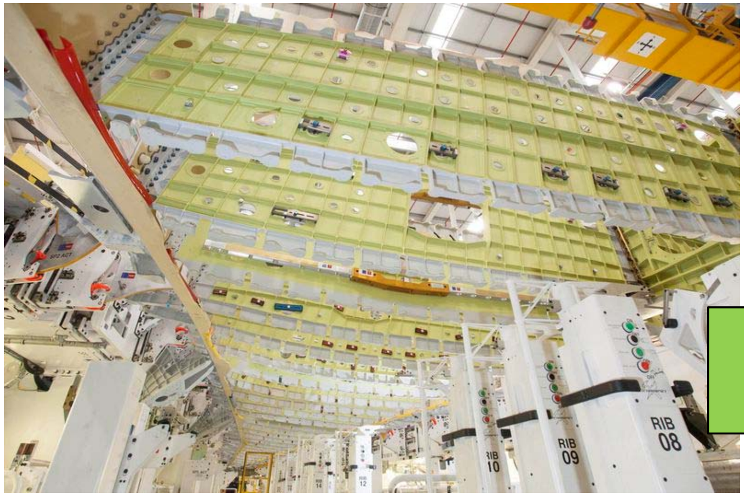
FRAMES

787

A350



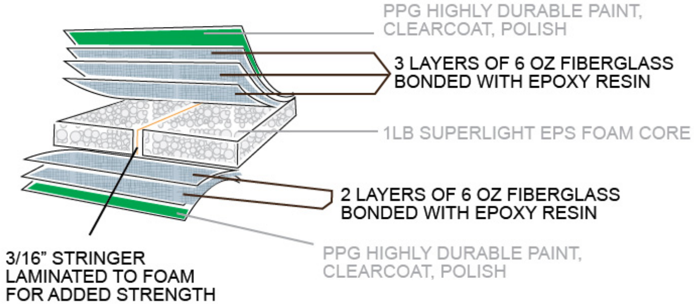
SKIN and STRINGERS



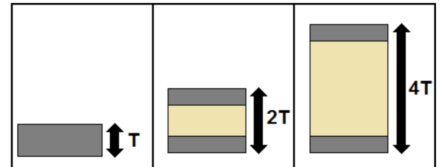
RIBS and SPARS

- ***Spars*** are thick I-beams (or, often, C-channels) that run from wingtip to wing root (and sometimes through the fuselage to the other wingtip). They're most important piece of structure on an airplane, supporting almost the entire weight of the airplane! Typically there is one just in front of the trailing edge (onto which we mount the aileron hinges and flap tracks/mechanisms) and one just behind the leading edge (where the slats attach), plus sometimes a third spar down the middle of the wing. Most tail fins, and most fighter jet wings, have 4+ spars.
- ***Ribs*** are airfoil-shaped plates that sit upright in the wings, oriented forwards and aft, keeping the airfoil cross-section of the wing and transferring lifting pressures from the skin to the spars.
- ***Wing stringers*** run just inside the skin from wing root to wing tip. They help the spars take wing-bending loads, and stiffen the skin to prevent buckling. In case of damage to the lower skin, they hold it together like a staple.
- ***Frames*** are hoop-shaped beams that help the fuselage maintain its circular cross-sectional shape. In case of damage to the skin, they hold the skin together like a staple (i.e. they help take pressurization loads). Fighters have non-circular frames. Frames that do not have a hole in the middle are called ***bulkheads***. At the back of the fuselage there is a dome-shaped Aft Pressure Bulkhead (i.e. the tail cone is not pressurized).
- ***Longerons*, or *fuselage stringers***, run just inside the skin from the nose to the tail. They help the skin take fuselage-bending loads (the nose and tail want to bend downwards) and pressurization loads, and stiffen the skin.
- Ribs and frames typically have "mouse holes" for the stringers, which run between small "***shear tie***" brackets.
- **The skin takes a lot of load!** It's not just there for looks and aerodynamics. The upper wing skins are in compression, the lower ones are in tension. The upper skins on the fuselage and horizontal stabilizer are in tension, the lower ones are in compression. Fuselage skins also see large stresses from pressurization: They're just thin enough so that the airplane won't "pop". This "stressed skin" approach allows the structure to be lighter.
- The fuel tanks are simply the wings skins (top and bottom), the spars (front and back), and some ribs (sides).
- ***Fairings*** are external components that are there to reduce drag. They serve no structural role other than holding their own weight and reacting local aerodynamic forces. Losing a winglet, a canoe fairing, a landing gear bay door, or part of the wing-to-body fairing, would not be structurally dangerous, it would just increase drag. Pretty much anything *else* you can see on the outside of an airplane, however, has a structural role!
- Of course, there is more to it than this. Landing gear, side-of-body, tail-fin fittings, engine mounts, keel beams, doors, cargo floors… are all very interesting. And military airplanes have some even more unusual structure.
- You don't really see "old-fashioned" trusses in most modern airplanes anymore, with a handful of exceptions such as some engine mounts, some Airbus ribs, and welded steel-tube cages in some homebuilt kitplanes.

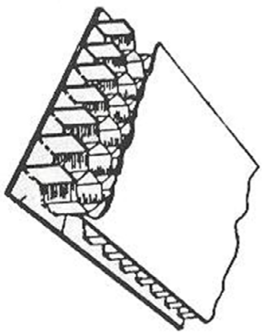
Foam Core & Honeycomb "Sandwich" Structure

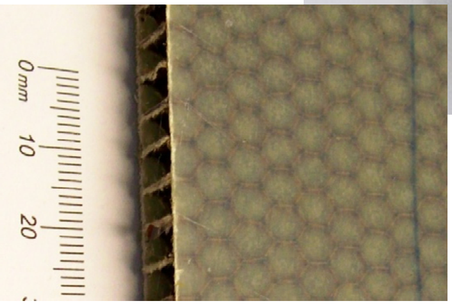


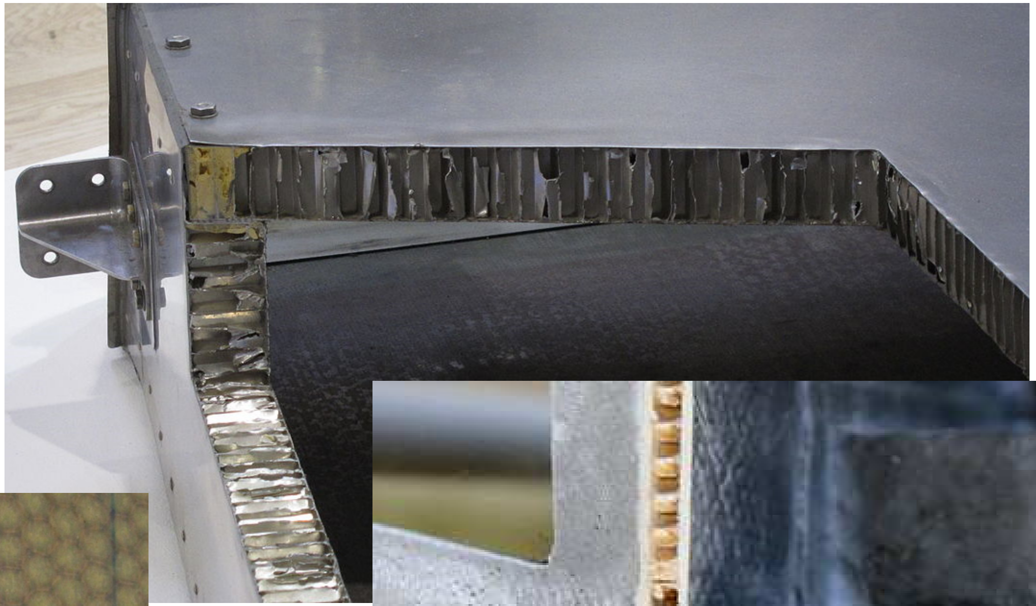
Metal, Fiberglass, or Carbon Fiber
Foam or Honeycomb
Metal, Fiberglass, or Carbon Fiber



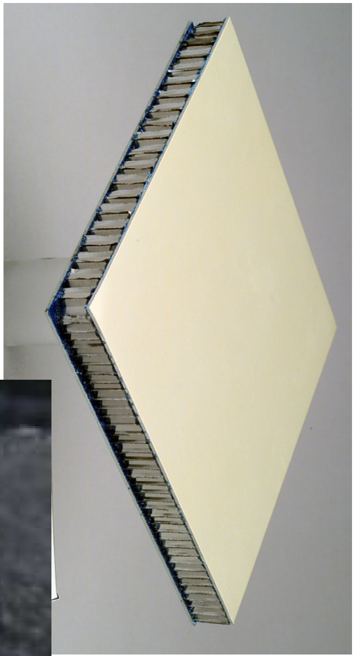
	T	2T	4T
Relative Stiffness (Bending)	1.0	7.0	37.0
Relative Strength (Bending)	1.0	3.5	9.2
Relative Weight	1.0	1.03	1.06







CESSNA 400



Foam Core & Honeycomb "Sandwich" Structure

- A sheet of metal, fiberglass, or carbon fiber, can be very easily bent or buckled. Two sheets glued together can still be bent or buckled fairly easily. But hold those two sheets apart, even by something flimsy like foam or honeycomb… VERY stiff!
- The honeycomb or foam is analogous to the thin metal webs in stiffened panels (holding the skin and the beam outer chords apart) or to corrugated cardboard… or to the cables and struts between biplane wings. They all hold things apart to add "depth" i.e. "height", which adds bending stiffness even if the structure is very lightweight.
- For a given weight, sandwich structure (foam-core or honeycomb) is stiffer than a stiffened panel, but typically not quite as strong. Modern high-performance airplanes use sandwich structure **mostly in parts like flaps, landing gear bay doors, and interiors (overhead bins, wall panels, lavatories…). These components are not expected to hold together their neighboring parts.**
- Another way to look at it: If lavatories and wall panels and overhead bins were made of aluminum, they would either be just as strong but much less stiff (i.e. "floppy"), or they would be just as stiff but much heavier, when compared to current sandwich structure.
- (A few unusual airplanes [e.g. XB-70, Beech Starship, Rutan Voyager, Boeing Condor, Cessna 400] have used honeycomb sandwiches on fuselage & wing structure, instead of using stiffened panels).
- Surfboards are foam core structure with a laminate skin. The image on the top left comes from a paddleboard website, made the same way as some airplane parts… and as some entire airplanes, such as the VariEze.

Foam Core “Sandwich” Airplanes

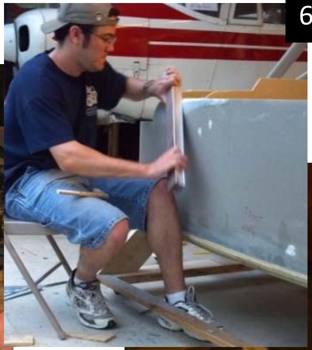
1

2

4

3

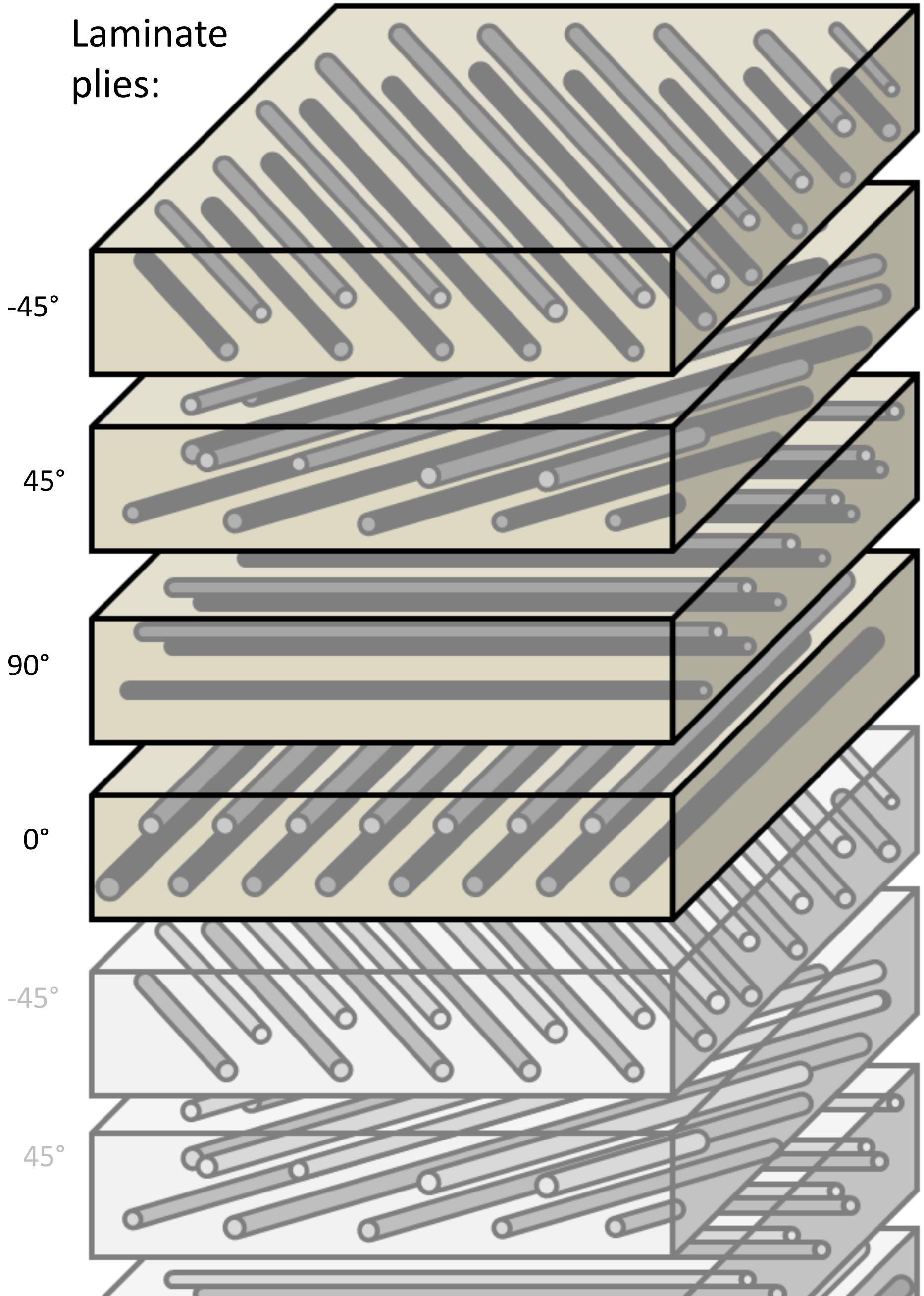
5



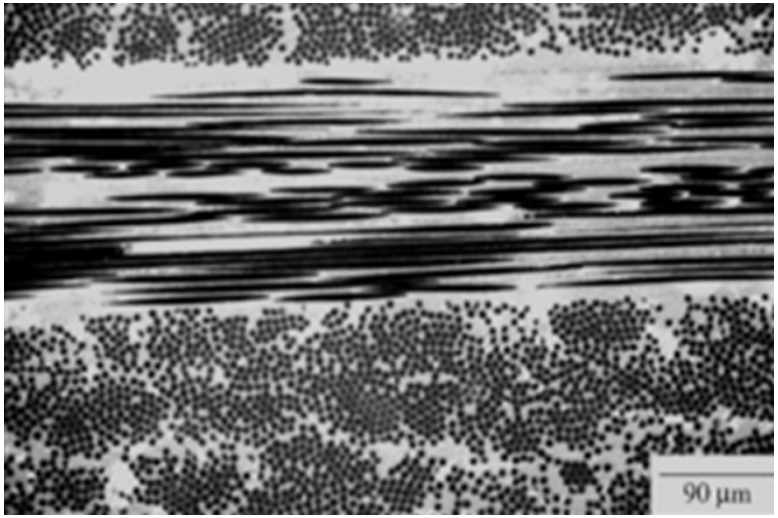
6

7

- Many gliders and homebuilt (FAA certification: "Experimental Amateur-Built") airplanes use foam-core fiberglass sandwich construction. The fiberglass skins do all the structural work, plus just a couple of spars and frames. No stringers. The wing foam is "one big rib".
- Started with German gliders in the 1950s and then popularized by Burt Rutan in the US in the 1970s-1980s (VariEze, Long-EZ, Quickie, Defiant, Solitaire…).
Used in modern kitplanes such as the Velocity, Cozy, and Raptor.
- It's easy to "sculpt" an airplane out of foam and then "wrap" it in fiberglass (or carbon fiber, if you can afford it). The foam is basically a mold for the fiberglass, which then just stays in the airplane because it's not too heavy ("fly-away tooling").
- Specifically: **(1)** Cut foam blocks with a hot wire or "carve" them with other foam blocks. **(2)** Cover the spar in layers of fiberglass and resin [see "4" & "5"]. **(3)** Put all the blocks in a jig and "glue" them with "micro" (fiberglass particles + resin). **(4)** Cut and lay down fiber-glass. **(5)** Pour resin onto fiberglass and spread until fiberglass is evenly "wet" with a thin layer of resin. Repeat "4" & "5" many times, once for each ply [layer]. **(6)** Sand the surface. **(7)** What you end up with is a rigid and strong fiberglass shell, with foam inside. More fiberglass is added to finish it up, e.g. to this aft wall where control surface hinges will be mounted. Each control surface is made the same way: Sculpt out of foam, cut and lay down fiberglass, apply and spread and smooth resin, repeat fiberglass and resin layers, sand, and finish/paint… almost always white, because heat from sunlight can cause the resin to deteriorate. (This isn't an issue with the more stable resins used by big manufacturers. Their chemistry only changes [cures or deteriorates] at very high temperature and pressure, i.e. in autoclaves).
- These "glass" airplanes end up a little heavier than they would be using stiffened-panel architecture… but can be built very quickly, have complex curvy shapes, and are extremely aerodynamic. A reliable way for amateur builders to achieve strong, durable structure and slick aerodynamics. Some of these airplanes still hold some fuel efficiency records.



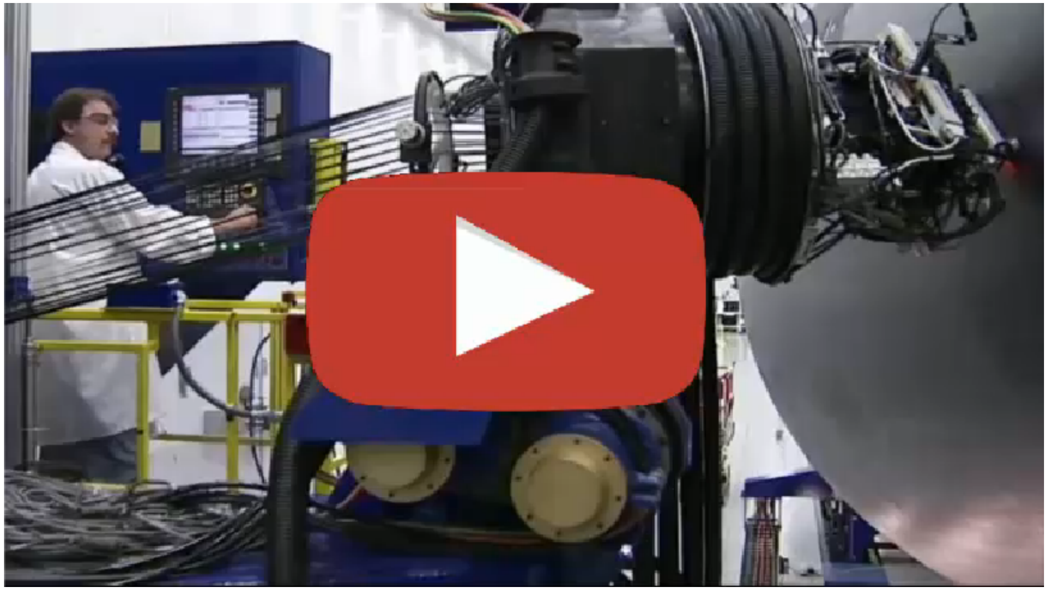
Fiberglass & Carbon Fiber Laminates

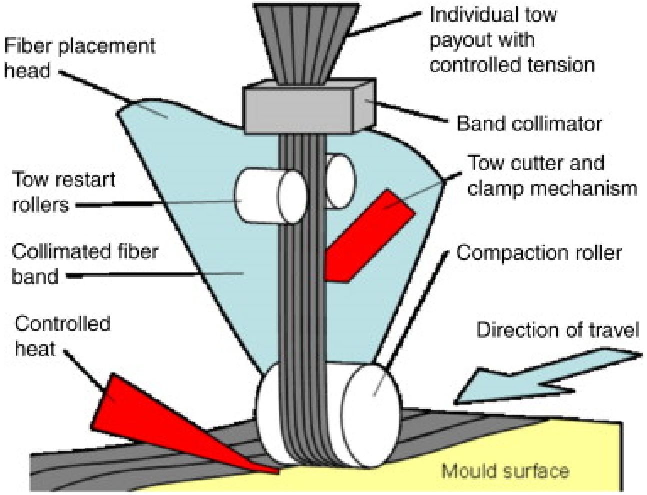


Fiberglass & Carbon Fiber Laminates

- A lightweight and relatively soft plastic ***matrix*** holds a bunch of stiff and strong ***fibers*** so that the overall composite is taller than the fibers alone. Roughly the same tensile capability as the fibers alone, but much higher stability (i.e. bending and compressive capability) due to greater depth. More plastic resin can be included to make the composite thicker (i.e. stiffer in bending, but heavier and not much stronger in tension). So the relationships between strength, stiffness, and weight can be precisely tailored.
- Plywood + resin have been used in aircraft structure since before WW1. Fiberglass was used in antennas and radomes in WW2, then in German gliders in the 50s, and in American homebuilts starting in the 1970s… but mostly as skin sandwiching foam cores. Starting around 1980, airplanes (e.g. Glasair) started using fiberglass in stiffened panels, with no foam or honeycomb.
- When the fibers are made of carbon (e.g. graphite), this is known as CFRP; ***Carbon-Fiber Reinforced Polymer***. It started being used in aircraft control surfaces in the 1960s and in primary structure around 1980 (e.g. F/A-18, AV-8B, NASA ACEE 737, L-1011, DC-10).
- Fiberglass and CFRP are ***laminates***, consisting of a series of layers ("laminas" or "plies"), each of which has fibers oriented at one angle (or sometimes at two perpendicular angles). Each ply will have 5 to 20 fibers through its depth (not just one or two as typically shown in diagrams like the one in the previous slide; See the microscope cross-section for a real image. Each ply is a few thousandths of an inch thick). As shown in the next slide, the material is built up ply by ply: Starting with a mold (or with a honeycomb or foam core), each layer is laid down on top of the previous layer, with the fibers (in a woven fabric sheet wet with resin, or along the length of pre-preg tape) laid down in the desired direction for each layer. The resin is then cured.

Carbon Fiber Laminates

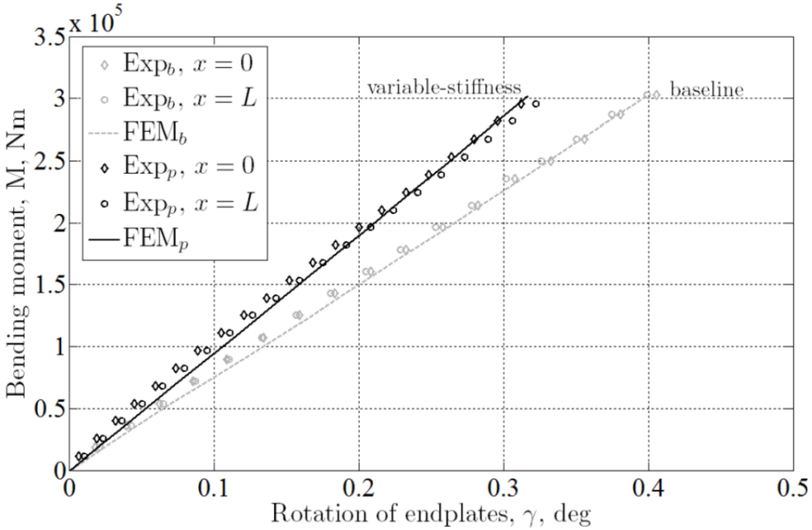


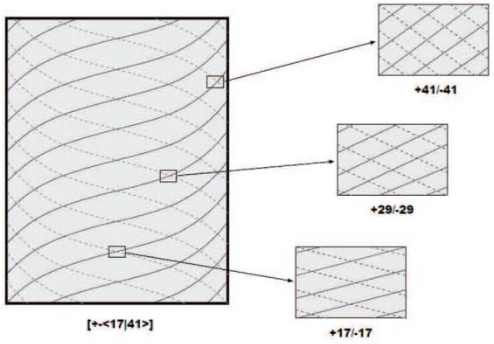


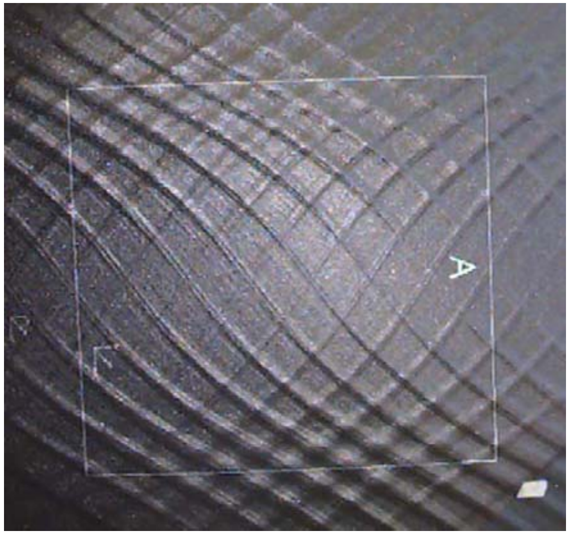
Carbon Fiber Laminates

- The simplest CFRP lay-ups are made of plies in sets of four: 0°, 90°, 45°, and 135°, repeated over and over. It has roughly the same strength in every direction ("quasi-isotropic") and is 10% to 20% superior to aluminum when it comes to the strength per weight of material.
- More interestingly, laminates can be tailored for more or less strength in different directions, depending on what fraction of the fibers is aligned with what angle. If all fibers line up the same way ("uniaxial", only 0° plies), then the material is much stronger than aluminum in that direction, and much lighter, but will have little strength in other directions. (This is ok for lower wing structure, for example, which almost only experiences tension along the wingspan). Pressurized fuselage skin has a hoopwise stress of PR/T and a lengthwise stress of PR/2T (look up *"stress in thin-walled pressure vessels"*) so one should wrap twice as many fibers hoop-wise as length-wise!

Composites – What's Next?







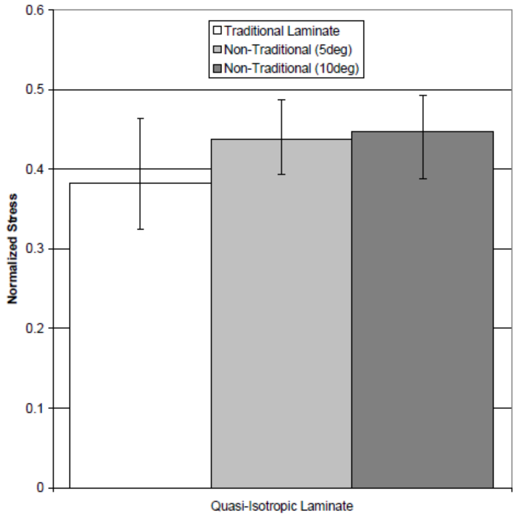
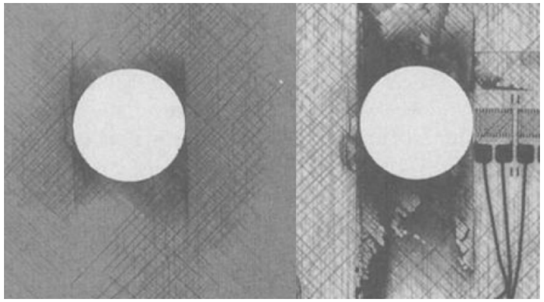


Figure 4.52 Average Quasi-Isotropic Single Shear Bearing Strengths

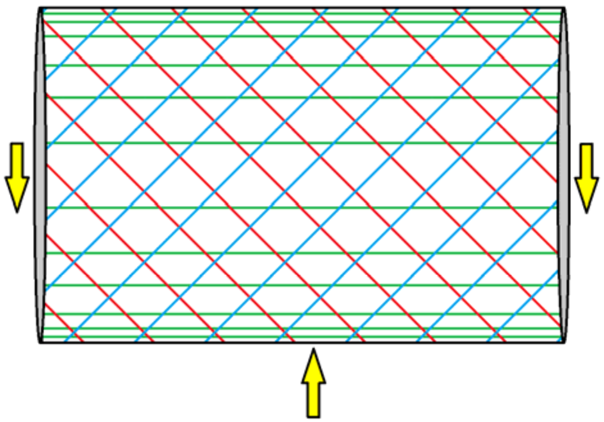


Composites – What's Next?

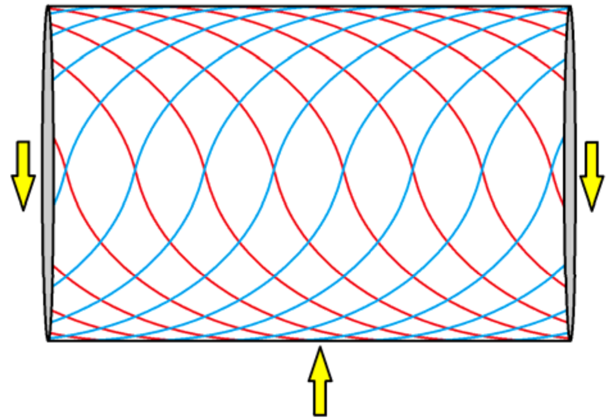
- Most laminates have all fibers going in straight lines. Some plies (layers) will be full of fibers at 0°, some at 90°, some at ±45°. This makes the design, fabrication, and mathematical analysis relatively straightforward.
- More and more airplane structure is built with at least some fibers at other angles, like 5°, 20°, or 60°. These "**non-traditional laminates**" are harder to analyze and manufacture, but offer greater strength with less weight, because the fibers can be more closely aligned with the loads, and there are fewer "extra" fibers (i.e. fewer fibers that are only there for stability or to prevent warping during cure).
- Why must fibers all be straight lines? Because it makes the structural design and analysis and fabrication less expensive. However, the structure ends up heavier than it would be if the fibers were curved. The future is to lay down fibers in curved paths, something known as **"curved tow paths", "tow steering", or "variable stiffness**". The principal stress at each location of a component is at some diagonal angle. Ideally, the fibers could be lined up with the principal stress direction at each spot.
- The following slide describes two examples of this technology.
- The following paper goes into just how much trickier it is to make structural components out of curved carbon fibers. These are the key challenges that must be overcome for this technology to be used: http://arc.aiaa.org/doi/pdf/10.2514/6.2005-2017
- Airplane structures got 10% to 20% lighter when engineers figured out how to switch from aluminum to carbon fiber. Once engineers figure out how to switch from conventional layups (carbon fibers in straight lines, with different combinations of fibers at 0°, 90°, or ±45°) to non-traditional laminate angles and curved tow paths, we could see another 20% drop in structural weight, or even more! **Just imagine: You could take airplane structure made of aluminum, and by replacing it with curved carbon fibers, you could cut its weight in HALF while preserving the same strength and stiffness!**

Curved Tow Paths: Two Examples

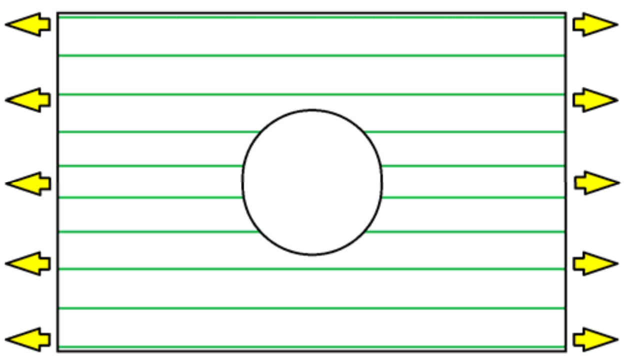
Present



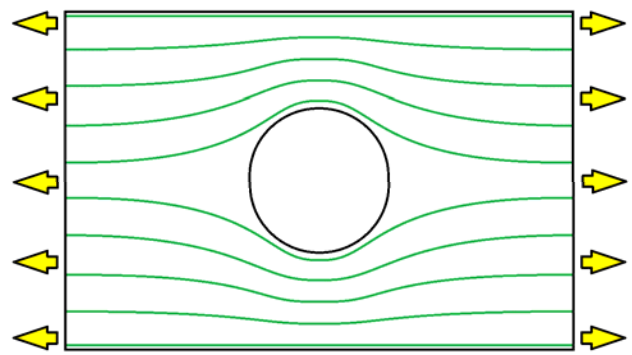
Future



Above: Vertical fibers ("hoop"-shaped to react pressurization loads) removed for clarity.
Below: Vertical and diagonal fibers (to react any loads in non-horizontal directions and to prevent splitting) removed for clarity



Present

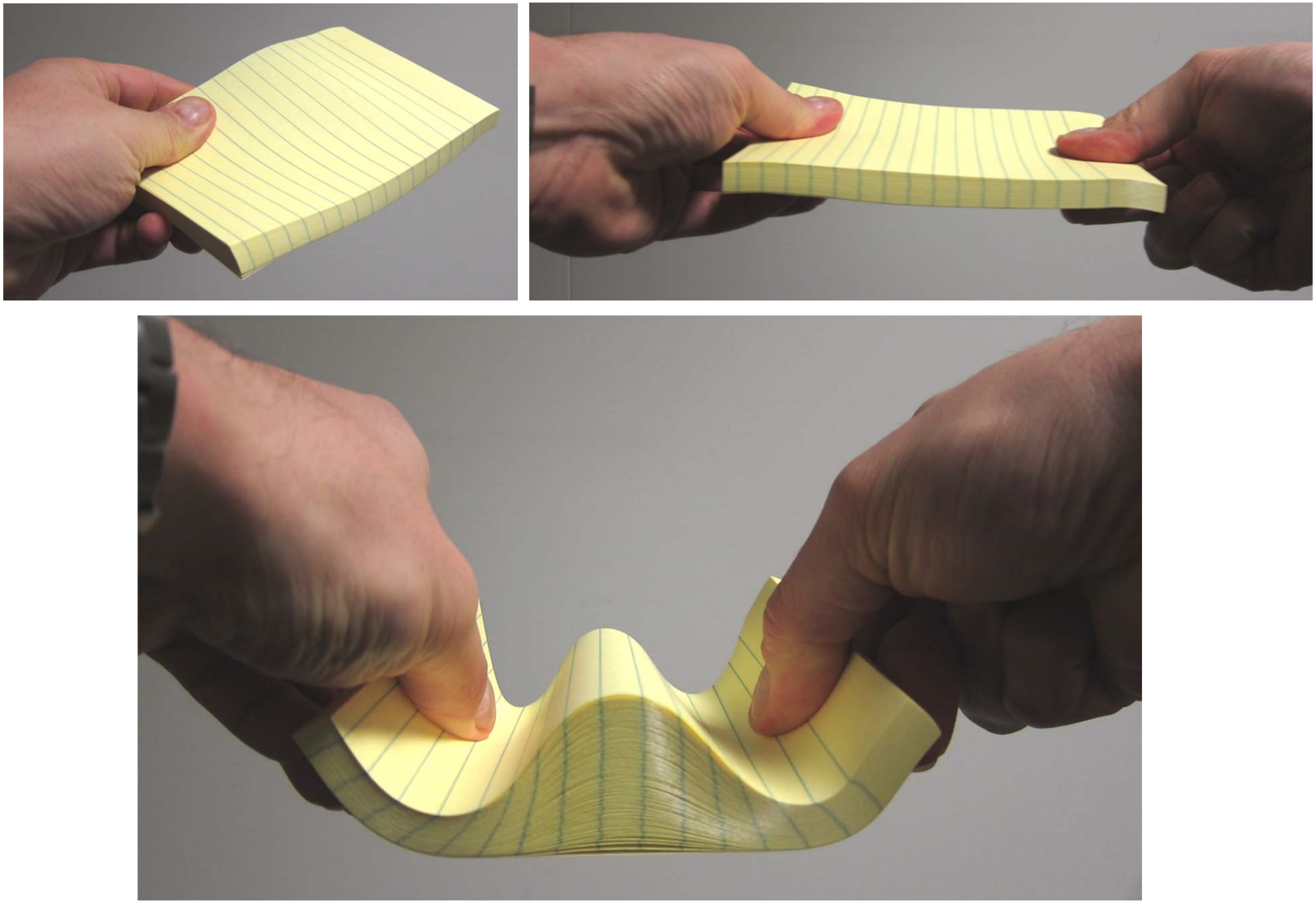


Future

Curved Tow Paths: Two Examples

- Ignoring pressurization effects for a moment: A fuselage is a cantilever cylinder in bending. The principal stress on the top is along the length of the fuselage, i.e. tension, and would be optimally taken by fibers going horizontally along the length of the fuselage. Same thing regarding compression along the bottom. The principal stress on the sides, however, is at a diagonal due to shear bending, and would be optimally taken by fibers along a diagonal angle, ideally a little closer to vertical. On composite airplanes, the whole fuselage (all the way around) has a bunch of fibers horizontally along the length of the fuselage, and a bunch of fibers at 45 degrees. (It also has a bunch of vertical fibers to take the "hoop load" from pressurization). **What if you had curved fibers that are an almost-vertical diagonal at the sides, but aligned closer to longitudinal (horizontal) at the top and bottom?** The following papers show that such curved fibers would increase the strength and stiffness by about 20%. This means that, using curved fibers aligned with the principal stress at each location, you could use 15%-20% less material than a conventional "0˚,90˚,±45˚" design, while keeping the same strength and stiffness.
  http://www.jeccomposites.com/news/composites-news/fibre-placed-variable-stiffness-composite-future-aerospace-structures
  http://repository.tudelft.nl/assets/uuid:46f2e44b-1a68-44f8-9633-79490a54e087/PhD_thesis_-_AWBlom.pdf
  http://reports.nlr.nl:8080/xmlui/bitstream/handle/10921/932/TP-2012-313.pdf?sequence=1
  http://issuu.com/fokker2011/docs/fokker2011
- Currently, fibers are laid down in straight lines, and then holes are cut for windows and doors and other openings. This leads to high stress concentrations, as fibers carry loads towards the edge of the hole, and then dump these loads near the edge of the hole almost at the "last minute" where the fiber abruptly ends. **What if fibers curved around openings?** They would carry their load uninterrupted, rather than forcing the material at the edge of the hole to pick up the load from all the cut fibers and transfer it to the cut fibers across the hole. That weak spot (the material around the edge of the hole, which carries the load between the cut fibers) would be almost eliminated. The first paper below predicts that, in theory, given a carbon-fiber panel with a hole: If the fibers curve around the hole rather than being laid down in straight lines and then cut when the hole is drilled, this could theoretically **increase the structural capability of the panel by almost 3 times!** (from 0.59 to 1.60). The 2nd paper shows, in the lab, that **the increase in strength is about 90.3% in compression and 55.5% in tension**. Either way: The component becomes MUCH stronger if the fibers curve around the hole rather than end abruptly at its edge.
  http://arc.aiaa.org/doi/pdf/10.2514/3.10697
  http://www.sciencedirect.com/science/article/pii/S0020768307002624

The Weakness of Laminates



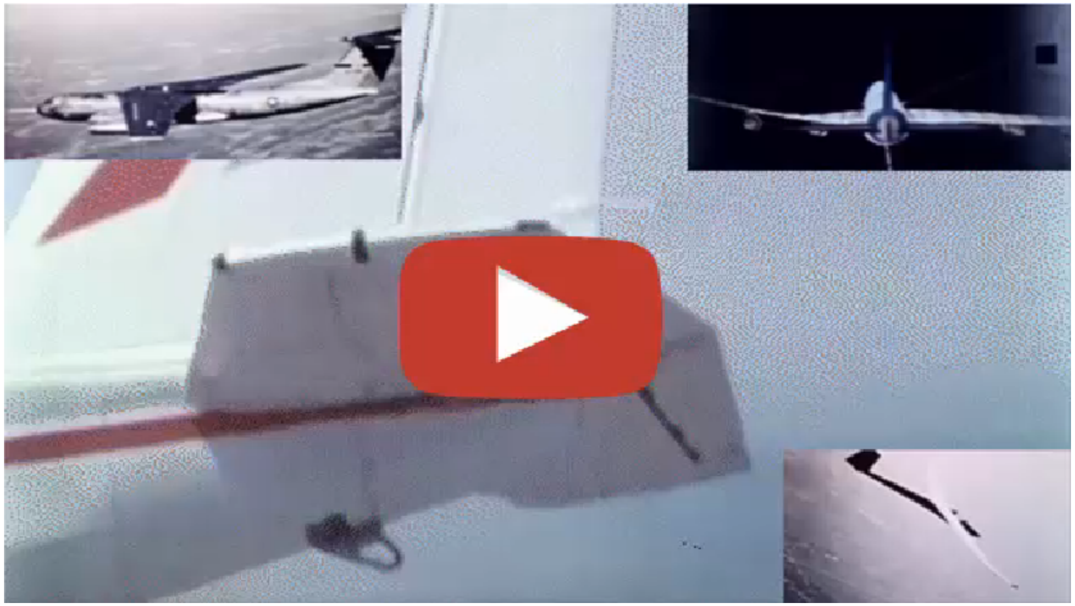
The Weakness of Laminates

- The "in-plane" strength of a laminate (i.e. being pulled in directions parallel to the plane of the layers) is very high.
- However, the "through the thickness" or "out of plane" strength (i.e. pulling the layers apart) is very low. (Not as low as in a pad of paper, where it is zero. But relatively low).

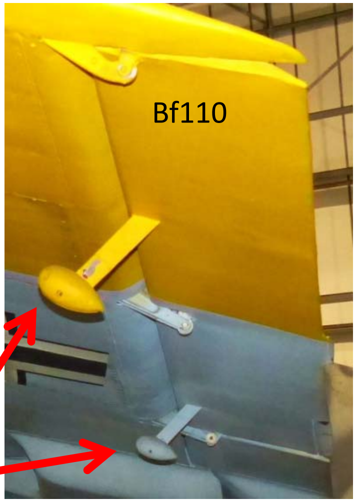
This means two things:

- (1) Components that experience tension in all three directions (up/down, left/right, forward/back) should be made of metal. A laminate can only be strong in 2 directions.
- (2) Whenever you bend something, the outside surface will be in tension, and the inside surface will be in compression. Try wearing long sleeves and bending your elbow: The outside stretches and the inside wrinkles. Now, when it comes to a solid piece of material being bent: The inner surface is in compression, so when it tries to buckle outwards (like the wrinkles on the inside of your long sleeve when you bend your elbow), it pulls the solid material outwards with it. ***Almost any material being bent experiences a stress trying to pull its two surfaces apart***, through the thickness. This stress is typically <10% of the tensile and compressive stresses along the surface. When dealing with metal beams (or anything else with roughly the same strength in all three axes), that through-the-thickness tension from bending is totally negligible. But when a laminate is bent, this through-the-thickness effect can cause delamination.
- (Try gripping a notebook or paperback book firmly at the spine and at the opposite side, so that the pages can't slide past each other… and bend the book. The pages delaminate near the middle: The ones on the "inside of the bend" pull away from the book by buckling. This is my favorite demonstration of why composites are tricky: You have to keep track of these small through-the-thickness forces trying to pull your structure apart, forces that pose no danger to metal structure).

Flutter



For a long collection of flutter videos, see http://youtu.be/egDWh7jnNic



MASS BALANCES

X-56

Plants flutter in the wind, as do flags. In strong winds, road signs and our clothes flutter.

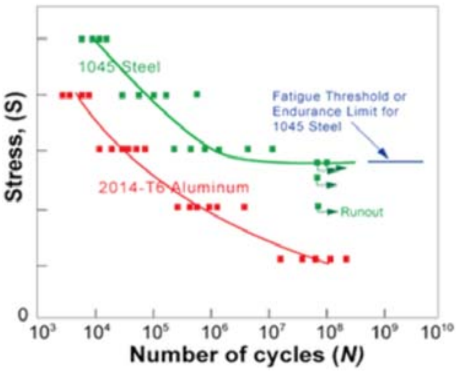
Flutter requires the following kind of "loop":

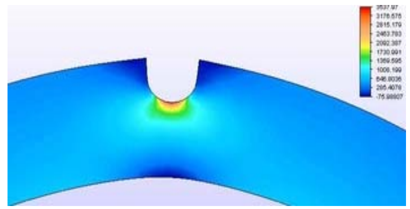
[1] Aerodynamic loading deflects something,

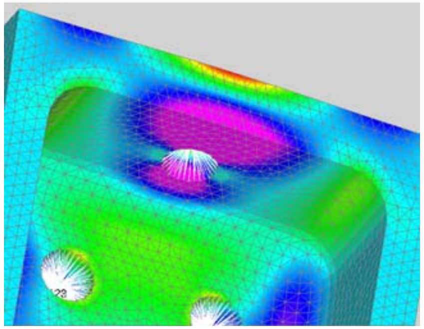
[2] In the deflected position, the aerodynamic loading is different (e.g. weaker or reversed), forcing the thing to go back to its initial shape (which causes [1] again).

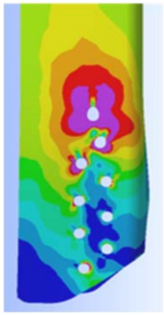
- It's like tennis: The ball's arrival on one side of the court causes a racket to hit it, that hit causes it to go to the other side of the court, the ball's arrival at the other side of the court causes a racket to hit it in the opposite direction, and now it's arriving on the first side again to re-start the loop.
- **Structures have resonant frequencies**. Vibration analyses are performed on new airplanes to predict those frequencies. Ground Vibration Tests are run to try to excite the frequencies, to check the predictions.
- These frequencies are generally higher than what can be induced in flight by aerodynamic forces. **But the faster you fly, the greater the forces, and the more quickly each part of the airplane is deflected**. (Again, tennis analogy: If the players hit the ball harder, the ball will go back-and-forth more times per minute, because pushing it harder makes it move faster). **If you fly fast enough, you can trigger resonant vibration frequencies, i.e. flutter, in the wings or tail fins!**
- Most subsonic airplanes have a "never exceed" speed, or VNE. It is typically set at 85% (for safety) of the speed at which flutter might be possible for the airplane.
- Flutter is often triggered **if the center of mass (of a wing, tail fin, control surface, flap, etc.) is behind the center of lift** (which happens easily: the center of lift is typically ~25% of the way back from the leading edge). Lift will not only bend such a part, but will then also twist it, changing the angle of attack, which in turn changes the lift, which changes the angle of attack… It's ok if lift changes the dihedral angle, but if it also changes the twist too much, flutter might happen. (Water flowing into trailing edges, and then freezing – thus shifting the CG aft – has caused Learjets to flutter and crash).
- **How to delay the onset of flutter until faster speeds?** There are a few ways. One is to take each wing, tail fin, control surface, flap, etc., and align its center of mass with its center of lift (which, again, is usually closer to the front). Control surfaces on many airplane have a mass balance (i.e. ballast) sticking out the front, or inside their leading edges.
- Another way to avoid flutter is to **make the structure stiffer.** Very stiff airplanes can go all the way to supersonic speeds without having to worry about flutter. But then, high temperatures or other compressibility effects will probably impose another "speed limit", the MMO, or Maximum Mach Operating speed.
- NASA is currently test-flying the X-56. Its slender glider-like wings have many small movable surfaces, like tiny fast-acting ailerons and spoilers, and many deflection sensors. When the onset of flutter is sensed, the surfaces automatically move to dampen the vibration. This flutter-suppression technology will hopefully allow fast jets to have thinner, more flexible, more glider-like wings, and the ability to fly faster without fearing flutter. In fact, the 747-8 had a minor flutter problem which was fixed this way, by deflecting the ailerons to aerodynamically slow wing vibrations, similarly to how a few gentle but well-timed pushes can help slow down a kid on a swing, over a few swings.

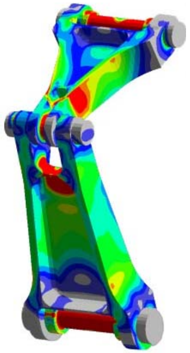
Fatigue

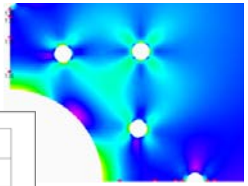

1045 Steel
2014-T6 Aluminum
Fatigue Threshold or Endurance Limit for 1045 Steel
Runout
Stress, (S)
0
10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10}
Number of cycles (N)

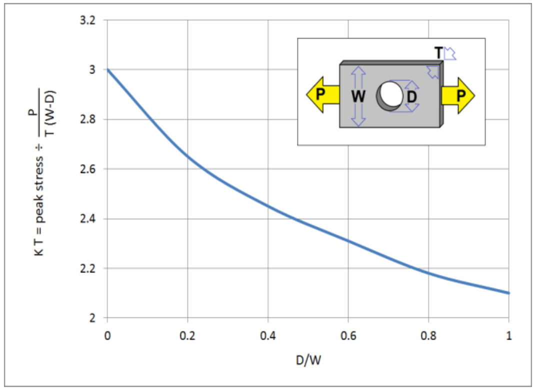


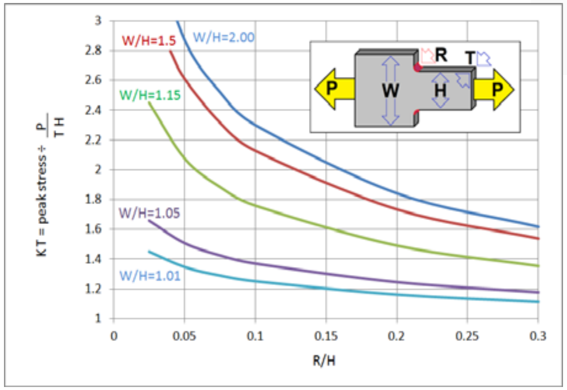


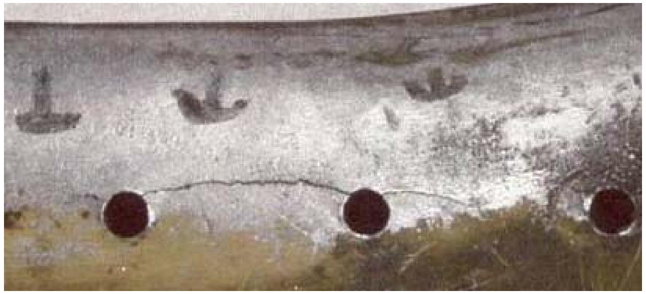


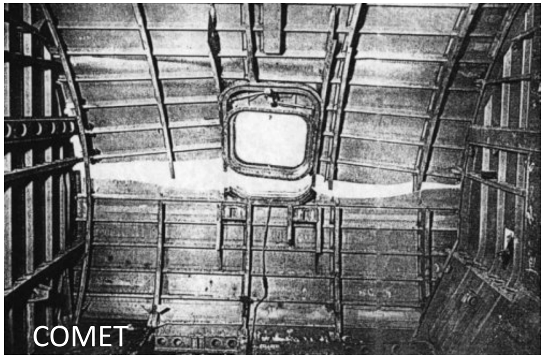




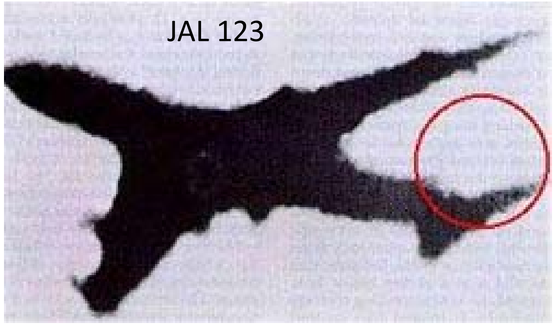

KT = peak stress ÷ P / T (W-D)
3.2
3
2.8
2.6
2.4
2.2
2
0
0.2
0.4
0.6
0.8
1
D/W
P
W
D
T


KT = peak stress ÷ P / T H
W/H=1.5
W/H=2.00
W/H=1.15
W/H=1.05
W/H=1.01
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0
0.05
0.1
0.15
0.2
0.25
0.3
R/H
P
W
H
R
T




COMET


ALOHA 243


JAL 123

- If I give you a paperclip, can you pull it apart? No. But if you bend it over and over, it eventually comes apart. ***Metal fatigues (cracks form and grow) when the stresses on it change over and over.***
- Most metal things – like building structure or the body of your car – experience roughly constant stresses. The local stresses don't change from tension to compression all the time.
- During each takeoff, the wings go from downwards-bending to upwards-bending: The lower wing structure goes from compression to tension, the upper wing structure goes from tension to compression… once per flight.
- As the airplane climbs, the fuselage pressurizes, putting the skin in tension like a balloon, once per flight.
- Some components are "sized" (i.e. their thickness and width are chosen) to withstand loads that only happen rarely, such as the vertical fin (rare side-slip maneuvers), the landing gear (really rough landings), and the floors and seats (belly-landing). So during everyday flying, stresses in these components are low… so they almost never fatigue. The fuselage, on the other hand, is pressurized almost identically on every flight, and is sized accordingly (the airplane is never going to fly into space), so it sees higher stresses every day and is slightly more prone to fatigue: Fuselage structure must have higher fatigue margins and be inspected more frequently for fatigue cracks. (More details about this in the next slide). The wing is somewhere in between: Sized to take loads that are worse, but not *much* worse, than normal everyday flying.
- ***Cracks nucleate at stress concentrations, e.g. holes and corners, and then grow over time.***
- ***The peak stress at the stress concentration "hot spot" typically determines the life of the component.***
- Fatigue experts have many **"stress concentration factor"** equations/graphs to find the peak stress of a feature as a multiple of the "average" stress… and **S-N curves** that tell you how many cycles to crack a material, as a function of the peak stress at each cycle. This is the basic idea behind fatigue analysis: Find the peak stress, then find the number of cycles. (Of course, it's not that simple…)
- Various measures can be used to extend the fatigue life of a component: **Avoid sharp corners** (e.g. the square windows on the deHavilland Comet) to reduce stress concentrations, use more durable materials, **manufacture smoother surfaces** ("Roughness" is just microscopic pits that will grow into fatigue cracks. Polishing a material effectively makes its S-N curve go up), use rivets and bolts that snugly fill their holes (so it's not just the corners of the fasteners pushing against just the edge of the hole, but rather a more distributed load), etc. Any point loads, very small radii, and/or other stress concentrations should be "smoothed out".
- For more information: http://www.faa.gov/about/initiatives/maintenance_hf/library/documents/media/aviation_maintenance/science10.pdf
  http://arc.aiaa.org/doi/pdf/10.2514/1.11717
  https://fenix.tecnico.ulisboa.pt/downloadFile/395142130354/disserta%C3%A7%C3%A3o.pdf
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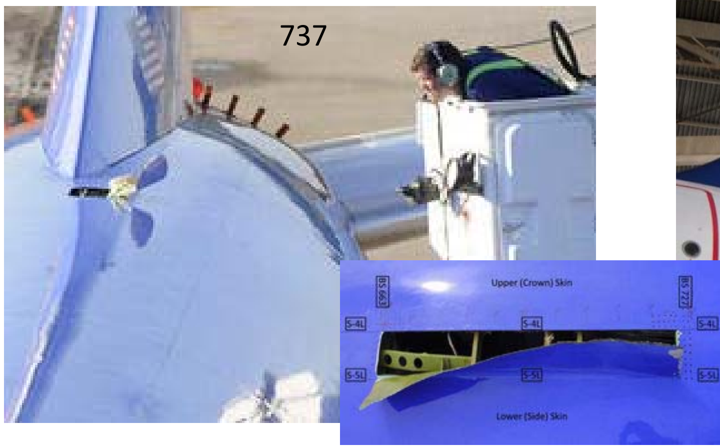
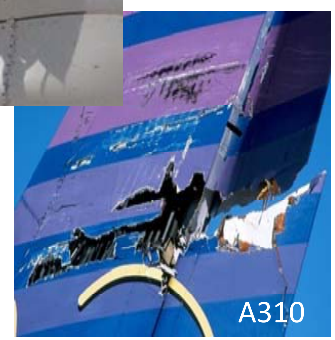
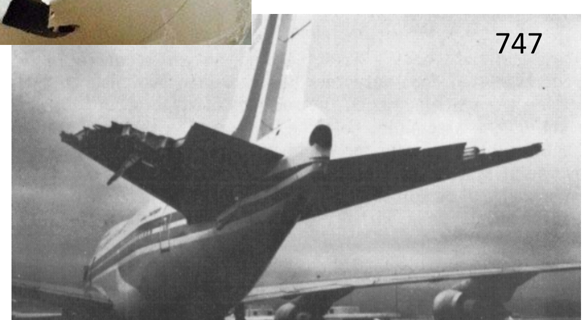
Damage Tolerance

FAIL-SAFETY (ROBUSTNESS):







FREQUENT
STRUCTURAL
INSPECTIONS

Damage Tolerance

(… where "damage" mostly means fatigue cracks, but also chemical corrosion, accidental damage, hail/lightning strikes, composite delamination, and all other forms of structural deterioration experienced by airplane components over time).

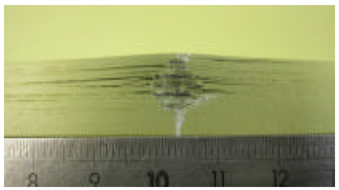
Note: At Boeing, I teach a couple of different one-week courses about fatigue and damage tolerance, for new engineers. I have ~1,000 slides on this topic and can probably lecture about it for ~80 hours. I am very proud of the fact that I was able to summarize it all into just ***two slides*** here!

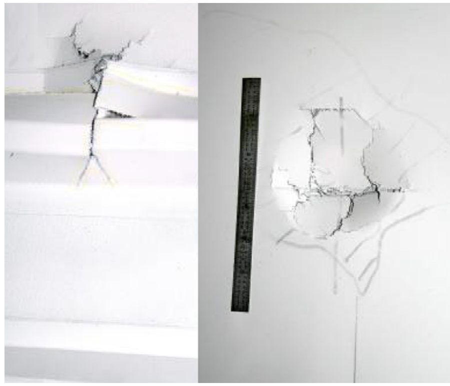
Requirements by the FAA, other regulators, and/or airplane manufacturers:

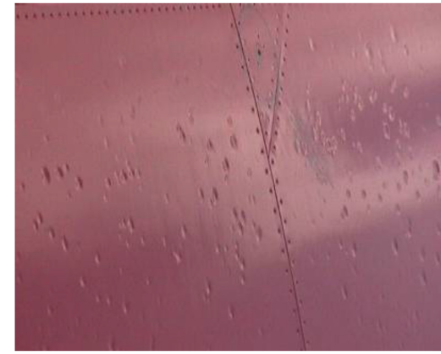
- Airplane structure must be fail-safe: **Any single component can fail and its neighbors must be able to take the load**, at least until landing. (Non-fail-safe components must have huge structural margins of safety, i.e. be ~50% thicker than they really have to be).
- The fatigue behavior of each piece of an airplane's structure must be predicted by analysis, as a function of the material, the stresses, and the surface quality during manufacturing.. Analysis, backed by test data and/or fleet data, must predict (1) for how long the structure will reliably have the full capability required to take its loads, and (2) if damage appears, how fast it might grow (worst case) from "detectable" to "dangerous".
- **All airplane structure must be regularly inspected by mechanics looking for damage**. Starting when? Depends on the results of the Durability Analysis, about how long the structure is expected to remain free of dangerous levels of damage. Then, once you start, how often do you inspect ? Depends on the Damage Tolerance Analysis, about how quickly damage could grow to a dangerous size after becoming big enough to detect…
- … and on how easy the damage would be to detect. Harder to detect? Check more often! This calculation (how often to inspect the structure in order to achieve some ***probability of detection***, given that there is damage) relies on decades of data about what % of airline mechanics actually detect what % of damage in structure, as a function of damage size and the inspection method used: visual, ultrasound, eddy current, etc.
- After many years, certain kinds of metallic structure are prone to having **cracks that are too small to detect but that already reduce the capability of the structure by enough to be dangerous**. For example: Landing gear is typically made of steels that are very strong and durable but that lose a lot of strength with just a small crack. And the fuselage has lots and lots of identical details that crack a little bit, rather than a few high-stress spots that develop just one or two long cracks early. This is known as Multi Site Damage / Widespread Fatigue Damage (MSD/WFD). Analysis must predict where and when this might happen. New airplanes must undergo full-scale fatigue testing to confirm the analysis (and to catch anything missed by the analysis). Structure prone to MSD/WFD must be replaced before MSD/WFD might happen, i.e. before undetectable-but-dangerous cracks might appear. This is expensive. If the additional profits from flying the airplane longer would not exceed the cost of this structural replacement, **the airplane is retired.**
- Note that airplanes are not *required* to be durable! Boeing and Airbus *could* build airplanes with very thin high-stress structure that starts fatigue-cracking within a year… or, if we prefer, build airplanes like a tank so they never fatigue (except due to manufacturing flaws, corrosion, accidental damage, hail, etc.). The airlines may want durable airplanes, or they may not: If fuel is cheap and maintenance hours are expensive, Boeing could build "tanks" that last for ever. If fuel is expensive and maintenance hours are cheap, Boeing could build planes that fatigue quickly. What we ***must*** do is understand how the structure will "age", how fast, and what structural maintenance inspections must be done to catch any damage before it's dangerous. **An airplane that fatigues more quickly is not any less safe than a "tank-like" airplane, if the structure is inspected for fatigue as often as is necessary to catch cracks in time.**

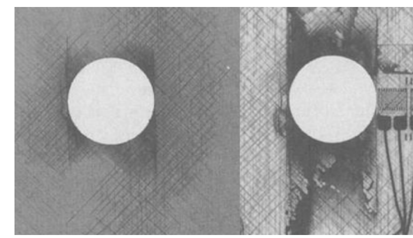
These lessons were learned the hard way ☹
- The Comet crashes in 1953-1954 showed the importance of ***fatigue analysis*** and ***fail-safety***.
- The Dan-Air 707 crash in 1977 showed that even fail-safe structure should be ***regularly inspected*** .
- The Aloha 737 crash in 1988 showed that fatigue cracks can be big enough to be dangerous AND too small to detect, due to ***MSD/WFD***.
- JAL 123 (1985) and China 611 (2002) showed that structural ***repairs*** can also cause crashes. They too must be fail-safe, analyzed for fatigue (including MSD/WFD), regularly inspected accordingly, etc.

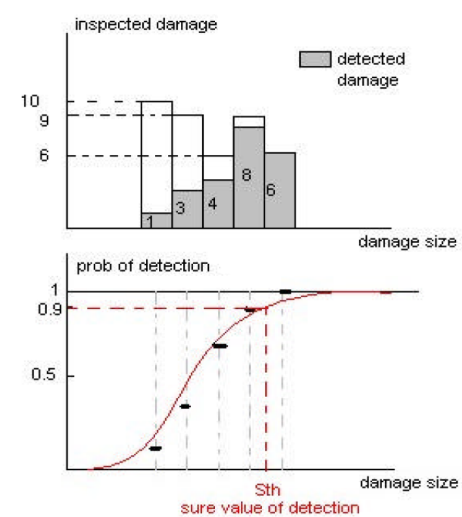
Composites "Fatigue" & Damage Tolerance











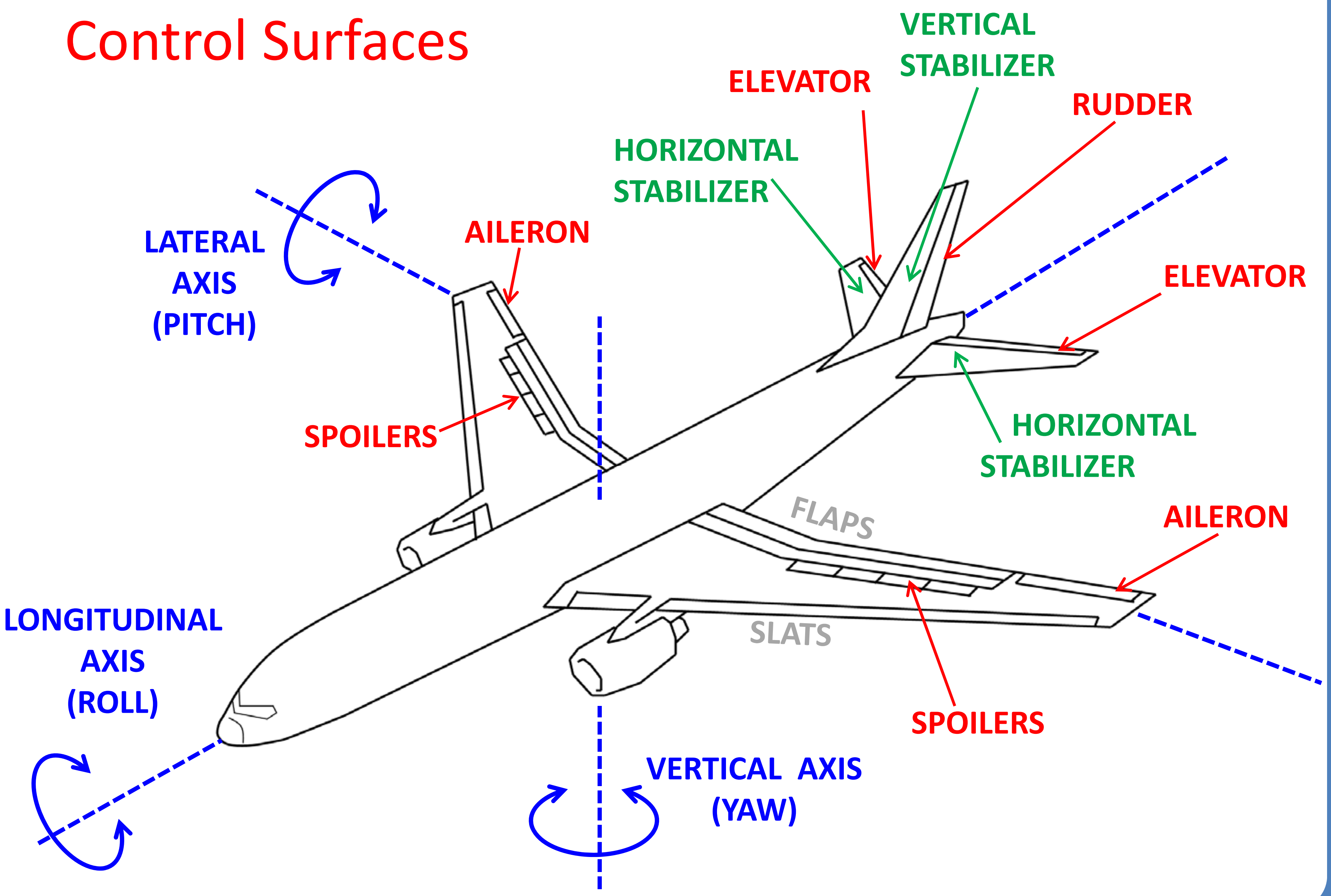
- Composites don’t fatigue-crack. “Damage” here means delamination, or breaking of the “matrix” (i.e. resin/polymer) or of the fibers. Sources of “damage” include fastener holes (e.g. when the hole is drilled, and/or when the fastener is pushed in, and/or over time due to high local stresses), manufacturing/ assembly operations (e.g. air bubbles caught between plies, forces from a stiffener sitting on a skin that is trying to thermally expand or contract during cure), and impact (e.g. a machinist or mechanic drops a tool on the part, fuel trucks or luggage carts hit the airplane, hail, bird strikes, runway debris / blown tires).
- For each of these sources of damage, the questions are: **Is it easily visible? Could it grow over time?**
- If damage occurs even at the worst possible spot in each composite structural component, either…
  - (1) stresses from flight must not be enough to cause the damage to grow, or…
  - (2) the damage may grow a little over the design service life of the airplane, but it must not grow enough to dangerously reduce the strength of the part, or…
  - (3) the damage must be easily visible, so it will be seen and repaired.
- The manufacturer determines what damage size is “easily visible”, and then designs their airplane structure in each area so as to be able to survive with damage that is “barely visible” or smaller.
- **For each piece of structure, the “damage size that might grow too much during the life of the airplane” must be larger than the “damage size that can be easily seen”. This must be shown by analysis or testing**.
- This requires not only knowledge about how damage in composite structure grows over time and about how that damage reduces the strength of the structure, but also about what damage can be reliably detected by machinists and QA in the factory and by airline maintenance mechanics.
- This is part of why large airplane manufacturers tend to shy away from bonded structural joints: They may be stronger and more durable than fastened joints, but are less inspectable. If a bonded structural joint connects thick components, there’s no reliable way to know whether it is disbonding.
- For more info: Airbus: https://www.niar.wichita.edu/niarworkshops/Portals/0/Airbus%20Composites%20-%20Damage%20Tolerance%20Methodolgy%20-%20Fualdes.pdf
  FAA: http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC20-107B.pdf part 8, and http://www.tc.faa.gov/its/worldpac/techrpt/ar10-6.pdf
  NASA: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150010963.pdf and http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100025547.pdf
  Boeing: https://www.niar.wichita.edu/niarworkshops/Portals/0/Thursday_1015_Fawcett.pdf
  and http://www.niar.wichita.edu/chicagoworkshop/Chicago%20Damage%20Tolerance%20Workshop%20-%20July%2019-21,%202006/Wednesday%20-%20Session%201%20Presentations/Boeing%20Transport%20Experience%20with%20Composite%20Damage%20Tolerance%20%26%20Maintenance%20-%20Fawcett%20%26%20Oakes.pdf

Balance, Stability, & Control

Balance, Stability, & Control

- Why do nearly all airplanes have tail fins?
- How can some airplanes fly without tail fins?
  Shouldn’t all airplanes get rid of them, since this is apparently possible?
- Why, in particular, do nearly all airplanes have downwards-loaded horizontal stabilizers? Isn’t that effectively like more weight?
- Where on the fuselage should the wings be placed?
- How is an airplane balanced if the engines are placed back near the tail?
- Why are airplane wings bent upwards?
- How do we ensure that airplanes naturally want to point “into the wind”, to point the way they’re flying, and to return to straight-and-level flight, using only aerodynamics and weight distribution, without needing constant pilot inputs or fancy control systems?
- How exactly do airplanes make turns?
- What is fly-by-wire? Envelope protection?
- Some airplanes have canards. Why? How do they work?

Control Surfaces



Fins:

- Vertical and horizontal stabilizers keep the airplane pointing the way it's going, like the tail fins on an arrow. If airplane starts to "slip", lift and drag on fins will push the tail to the back so it's downwind of the nose again.

Control surfaces:

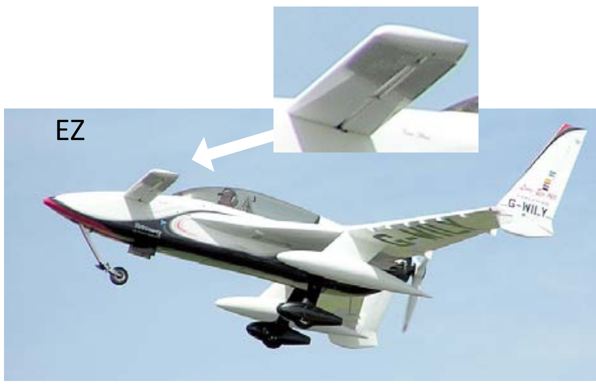
- Ailerons near the wingtips (and often spoilers) for roll control: The main way to turn the airplane is to bank it in the direction you want it to turn, which points the lift in that direction, causes the airplane to slip in that direction, and pushes the vertical stabilizer back, making the nose point the way the airplane is banking.
- Elevators at the back of the horizontal tails for pitch control: i.e. for making the airplane fly at the desired angle of attack, for climbing and descending (and turning tighter)
- Rudder at the back of the vertical tail for coordinating the turn, i.e. for turning at the correct rate to match the bank angle, or for intentionally slipping or skidding during crosswinds, forward slips, or aerobatics.

Control Surfaces (Unconventional)

F-22 STABILATORS

B-2

N-9M



EZ

YF-23

BEECH BONANZA

F-35

RV-12

PIPER CUB

Control Surfaces (Unconventional)

Fins (unconventional):

- V-Tail acts as both vertical and horizontal stabilizers
- Canards are horizontal stabilizers near the front and typically also contain the elevator. More about them soon (slides 238-239).
- Winglets can be the vertical stabilizers if the wingtips are far enough aft
- Stabilators: All-moving horizontal fins, common in fighter jets. Stabilizer, elevator, AND aileron!

Control surfaces (unconventional):

- Elevons: Typically in the horizontal tail. Work together as elevators, differentially as ailerons.
- Flaperons & drooping ailerons: Work differentially as ailerons, together as flaps.
- Ruddervators on V-Tails: Pretty self-explanatory

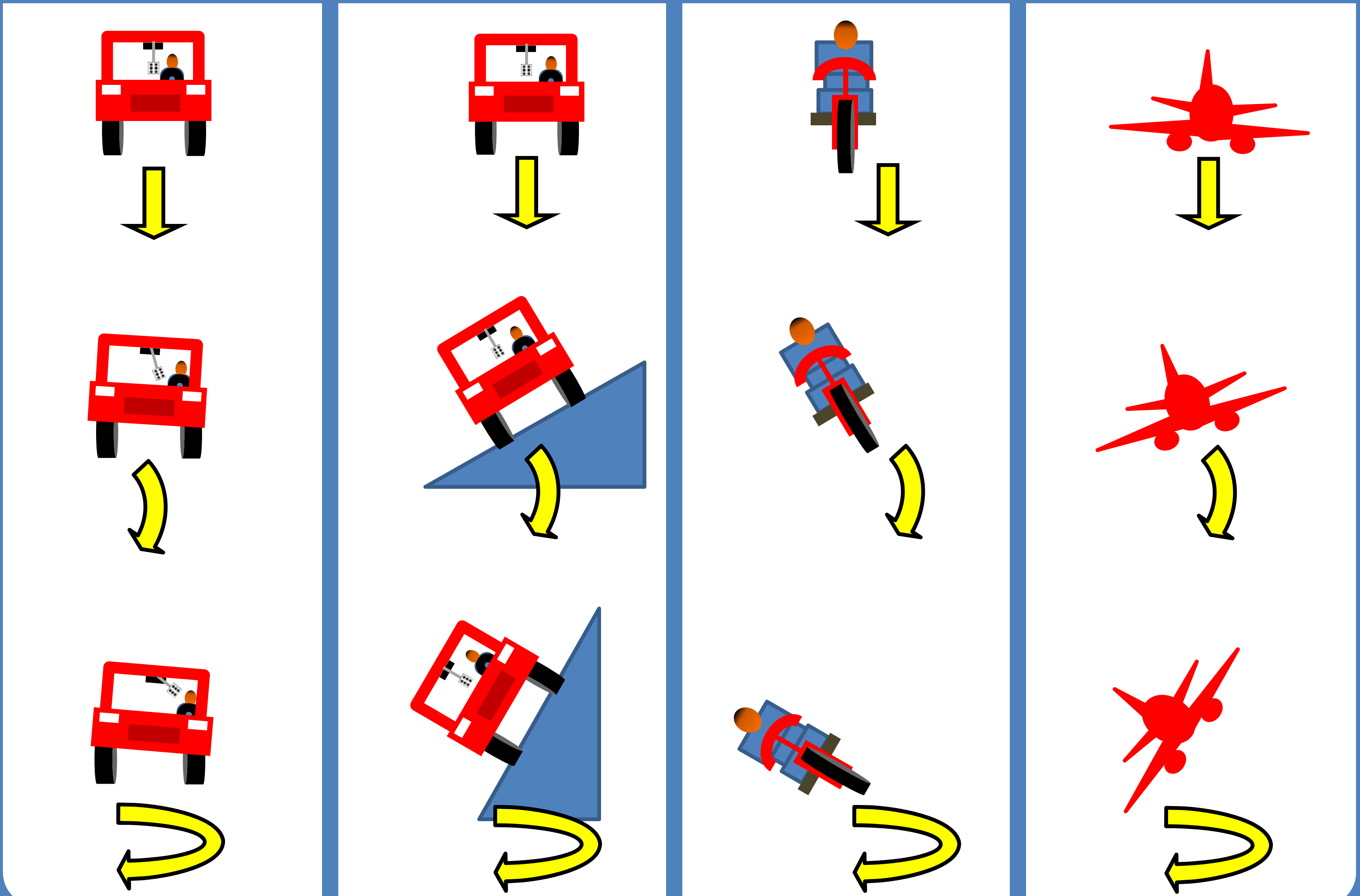
- Drag rudders / split ailerons: Can "split open" at the wingtip (top of aileron goes up, bottom of aileron goes down) to act as an air brake. If this is done at only one wingtip, it acts as a rudder, pulling that wingtip backwards and swinging the nose towards it. This is mainly used on flying wings & stealth airplanes.

Banking into Turns

Banking into Turns

- When you are in a car and it makes a tight turn, you feel a "centrifugal force" pushing you to the outside of the turn.
- Some racetracks, on-ramps/off-ramps, overpasses, and car test tracks are ***banked***. This way, the "centrifugal force" pushes the car into the ground, rather than trying to slide it.
- For the same reason, cyclists must ***bank*** or lean into their turns.
- The tighter the turn, the more banking is required to keep all forces (the sum of gravity plus the centripetal acceleration) pushing the rider straight down onto the seat, not sideways.
- As we'll see in the next slide, the exact same thing applies to airplanes.

Coordinated Turns



- The tighter the turn, the more banking is required to keep all forces (the sum of gravity plus the centripetal acceleration) pushing the rider straight down onto the seat, not sideways.

- Imagine a pendulum (e.g. fuzzy dice) hanging from the rear-view mirror of a car.
  A slight turn will cause the pendulum to swing out slightly.
  A tight turn will cause the pendulum to swing out at a high angle.
- So a slight turn in a slightly-banked track would make the pendulum appear to be “vertical” in the car, i.e. all forces would be pushing the driver “straight down” into the seat and not sideways.
- Similarly, tight turn in a steeply-banked track would make the pendulum appear to be “vertical” in the car, i.e. all forces would be pushing the driver “straight down” into the seat and not sideways

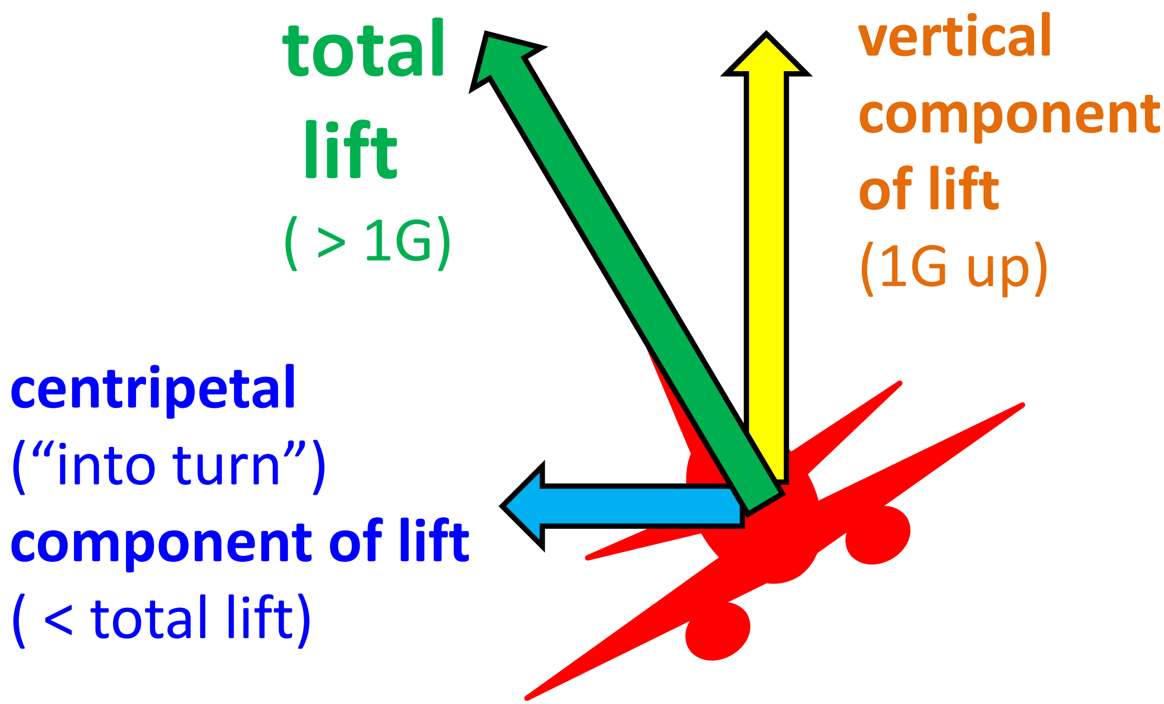
- For the same reason, cyclists lean slightly into slight turns, and lean steeply into tight turns.
- If you wear a necklace while driving, then make a tight turn, the necklace will swing outwards.
  But if you wear a necklace on a bike and make a tight turn, the necklace will continue to hang “down”.

- [Another fun analogy, this one not in the previous slide: A waiter walking in a non-straight path must bank the tray so that dishes don’t slide around and drinks are not spilled].

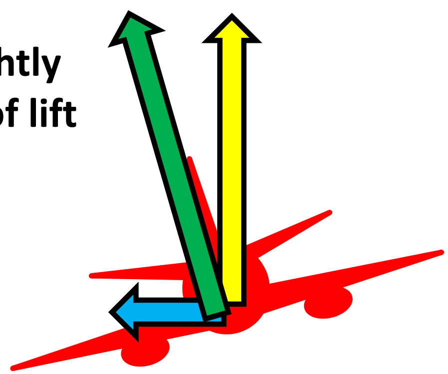
- And for the same reasons, airplanes bank slightly into slight turns, and bank steeply into tight turns: So that all occupants feel only “vertical” forces (in their perspective) during turns.
- This way, pendulums inside the airplane appear vertical, and no one spills their drinks.
- These are called “coordinated” turns. How much the airplane banks (using the ailerons) is ***coordinated*** (not too much, not too little) with how tight the airplane makes a turn (using the rudders and pulling up on the joystick/yoke).
- Too much rudder / not enough banking causes things to slide outwards (“skid”) like in a car.
  Too much banking / not enough rudder causes things to slide down into the turn (a “slip”).
  So: What does a rudder do? “It controls yaw”? Not quite: It ***coordinates turns***.

- When asked “Why do airplanes bank into turns?” or “Why don’t airplanes just turn with the rudder?”, you can answer “Because they were invented by two guys who used to make bicycles” ;]

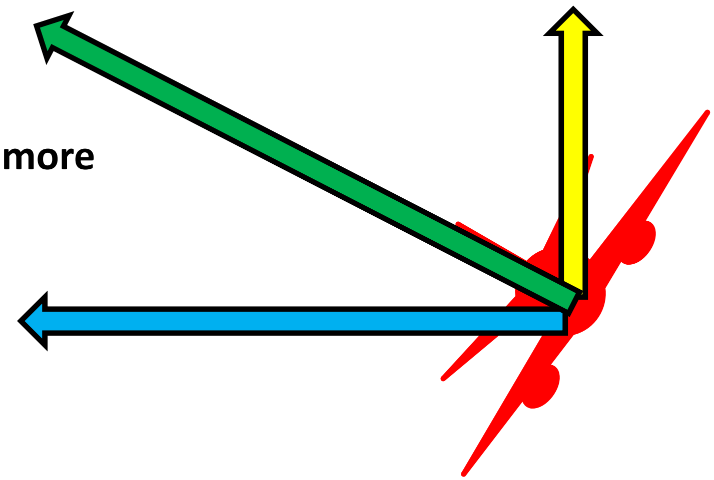
Turns and "G"s



Shallow turn:
Needs only slightly more than 1G of lift



Steep turn:
Needs much more than 1G of lift

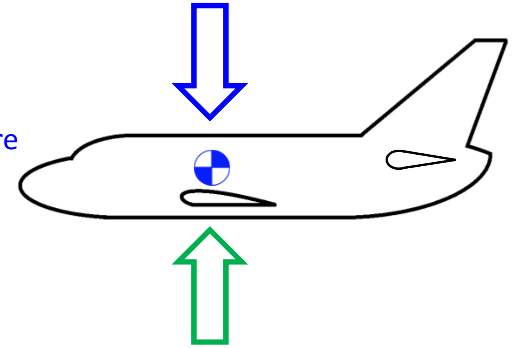


Turns and "G"s

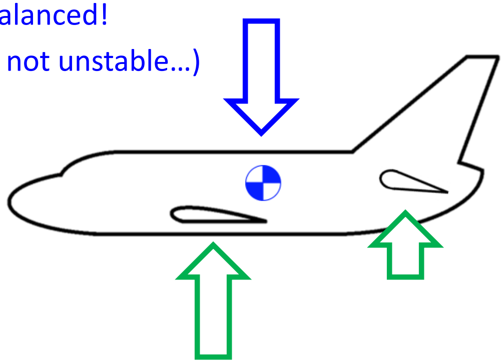
- As we just saw, airplanes turn by banking into the direction the pilot wants to go.
- The lift now pulls the airplane not only vertically away from the Earth, but also horizontally into a turn.
- To maintain altitude, the vertical component of the lift must remain at 1G. So the steeper the airplane banks, the more total lift it must generate. So more bank angle means more Gs and a higher angle of attack (and more induced drag, and thus probably a little more power if the speed is to be maintained).
- Each airplane, at each speed and altitude, has a certain "max sustained G" that it can pull without slowing down, which depends on its excess thrust at that speed and altitude… and a "max instantaneous G" that it can pull, which depends on how high an alpha can be achieved without stalling or breaking the wings.
- The rate and radius of the turn depend on the horizontal component of the lift. What the airplane's wings (and occupants!) experience, however, is the total (diagonal) lift. The vertical component of the lift is always 1G, if altitude is to remain constant.

Balance

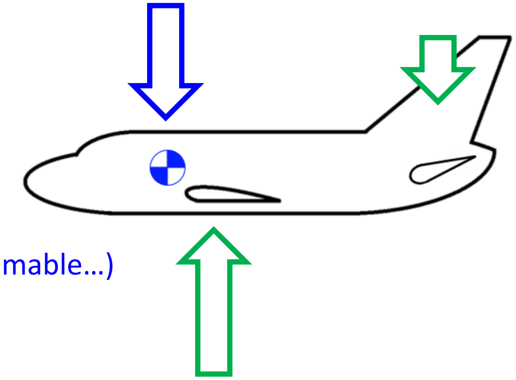
CG right where wings are
Tail does no lifting.
Airplane balanced!



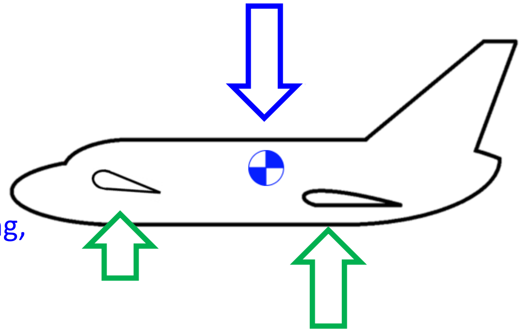
CG behind where wings are?
Tail lifts up a little.
Airplane balanced!
(Hopefully not unstable...)



CG ahead of where
the wings are?
Tail pushes down.
Airplane balanced!
(Hopefully still trimmable...)



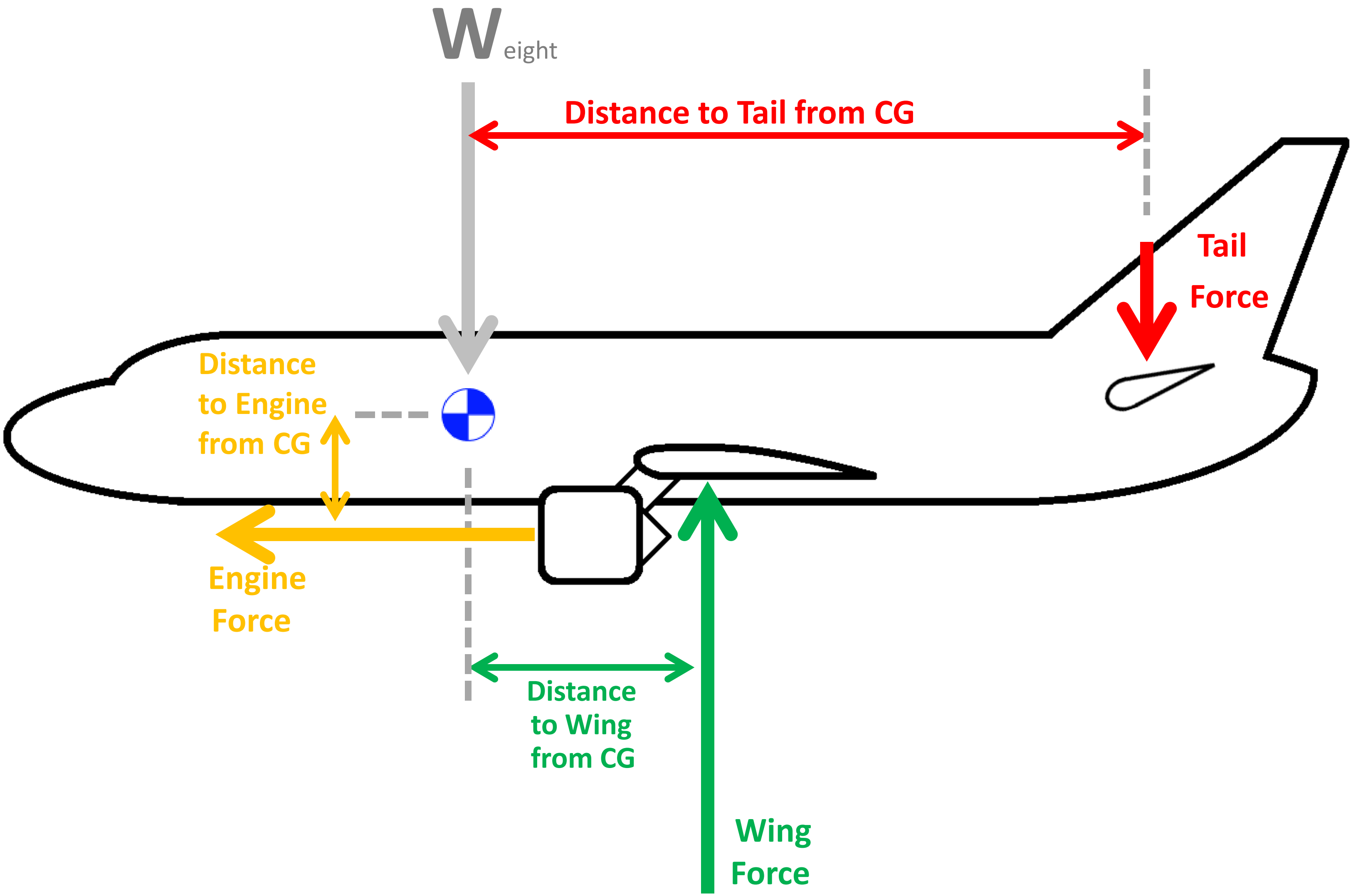
Canard airplane?
CG must be ahead of the wing,
canard must push up.
Airplane balanced!



Balance

- Where should the Center of Gravity (CG) of an airplane be?
- A pretty good initial guess might be: Right where the wings are. This way, the wings do all the lifting, and the horizontal tail does zero lifting.
- If the CG ends up a little too far aft, then the tail can do a little bit of lifting, for balance.
- If the CG ends up a little too far forwards, then the tail can do a little bit of pushing downwards, for balance.
- If you have a canard airplane, then you have no choice: The CG must be ahead of the wings and behind the canard.
- If you think about this a little bit:
  Wing lift force = Weight + Tail down-force
  Also:
  wing lift force x distance from CG to wing = tail lift force x distance from CG to tail

Balance



Weight
Distance to Tail from CG
Tail
Force
Distance
to Engine
from CG
Engine
Force
Distance
to Wing
from CG
Wing
Force

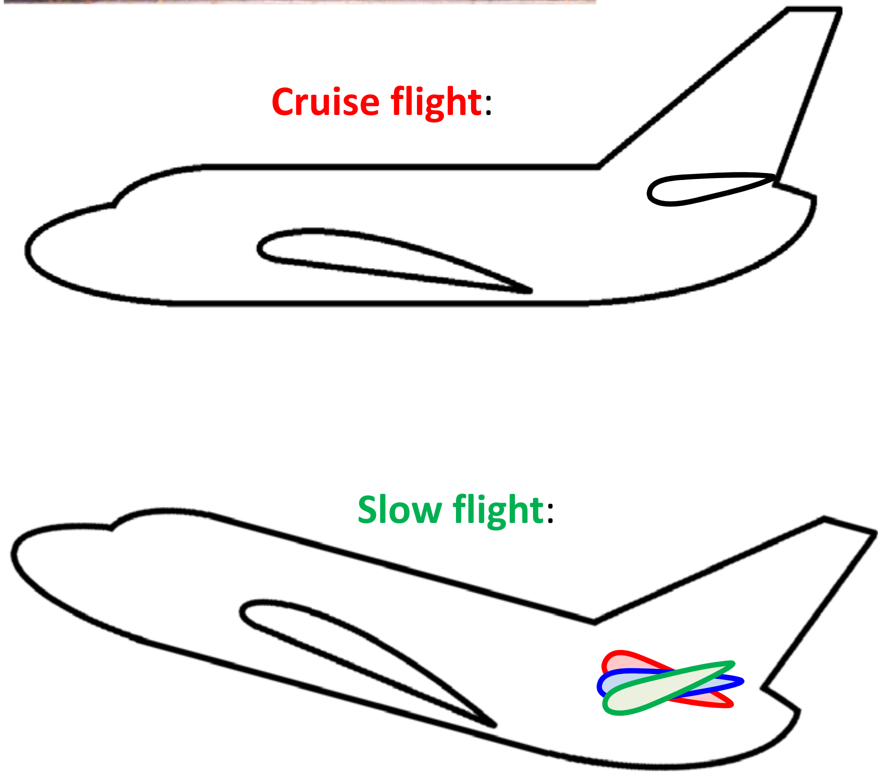
Balance

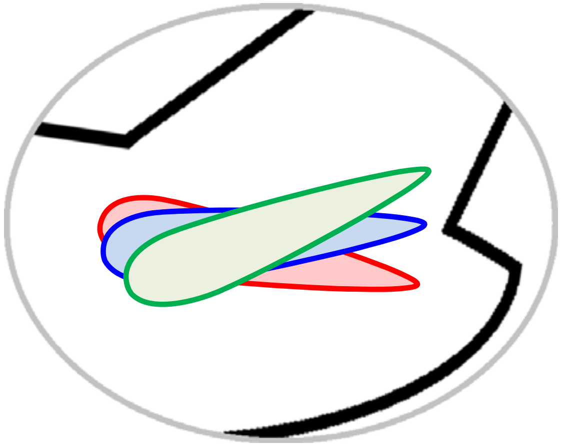
- Imagine that the airplane is "pinned" at the CG, and that the forces (lift on the wings, down-force on the tail, and engine thrust) are trying to rotate it either nose-up or nose-down.
- If your engines are low, then during climb and cruise, the engines supply some nose-up moment, so the tail does not have to push down as hard to balance the airplane. (But during descent, at low power settings, the tail must supply that moment without much help from the engines). (Some simple airplanes, such as powered parachutes and some RC models, use engine thrust to control pitch. If you lose thrust, you're going down!)
- "Balance" means that, **in order for the airplane to not pitch up or down, all of the moments (i.e. forces times distances) around the CG must add up to zero**. (Moments in one direction – either nose up or nose down – should be negative).

wing lift x wing distance to CG + tail down-force x tail distance to CG + engine thrust x engine distance to CG = Zero

- So given an airplane and its engines, wings, and tail… Where can the CG be? There are two very important limits, related to how hard the tail can push down:
  - (1) If the CG is too far forwards, the tail might not be able to push down enough to balance the CG, ***and*** to trim for high-alpha (e.g. slow) flight, ***and*** to push the nose up when required (e.g. on takeoff).
  - (2) If the CG is too far aft, the tail might end up at a higher angle of incidence (or, the canard might end up at a lower angle of incidence). This would make the airplane unstable in pitch!
- Both these factors are discussed in detail over the next few slides.

Trim





Trim:

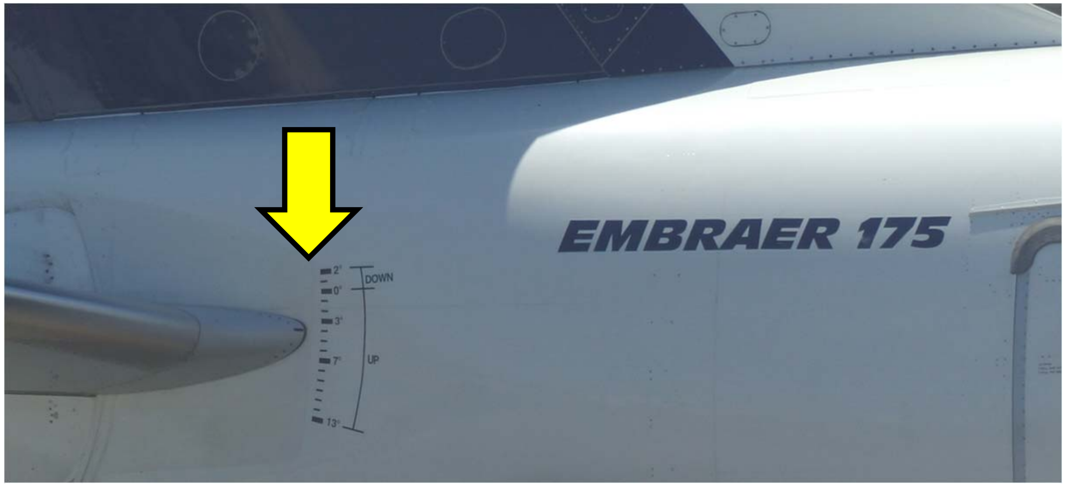
(1) Cruise setting.

(2) Same alpha as cruise

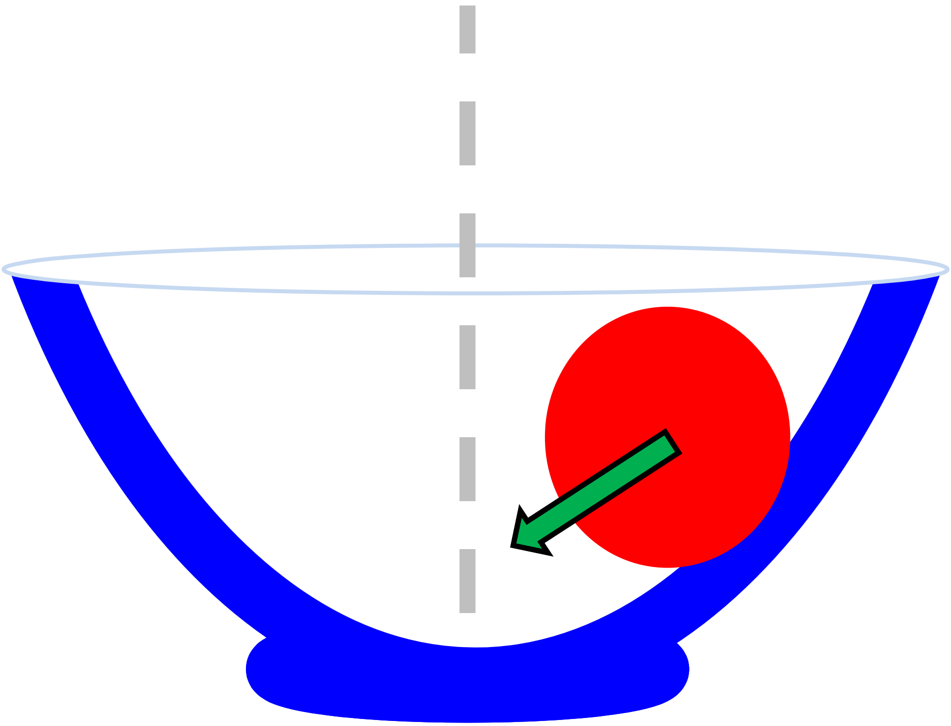
(3) More negative alpha required to generate enough down-force at slower speeds

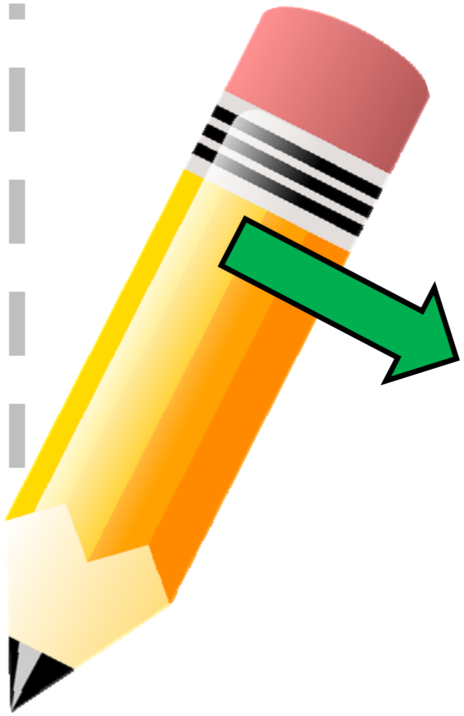
Trim

- Say that the horizontal stabilizers are pushing down(which they typically are, for stability).
- The more slowly the airplane flies, in order to supply the correct amount of lift, the higher an alpha is needed by the wings… AND by the stabilizers!
- If the wings and horizontal stabilizers could be swiveled about their spars, the wings would just tilt up and the horizontal stabilizers would just tilt down, while the fuselage remained horizontal.
- But the wings cannot be swiveled up (except in the F-8 and B-51). So, while flying slowly, the whole fuselage must tilt up, along with the wings. But the elevators and/or horizontal stabilizers have to deflect down: not just enough to get back to the original angle of attack, but even ***further***, in order to generate the required down-force at slower speeds. (This is even more true once the flaps come down: They shift the wings' center of lift aft, i.e. they try to lift the tail because they are so far back. The horizontal stabilizers must "fight" them).
- So, during slow flight, the horizontal stabilizers (and the elevators, on smaller airplanes) need to deflect downwards (i.e. to be "trimmed nose-up") significantly.



Stability

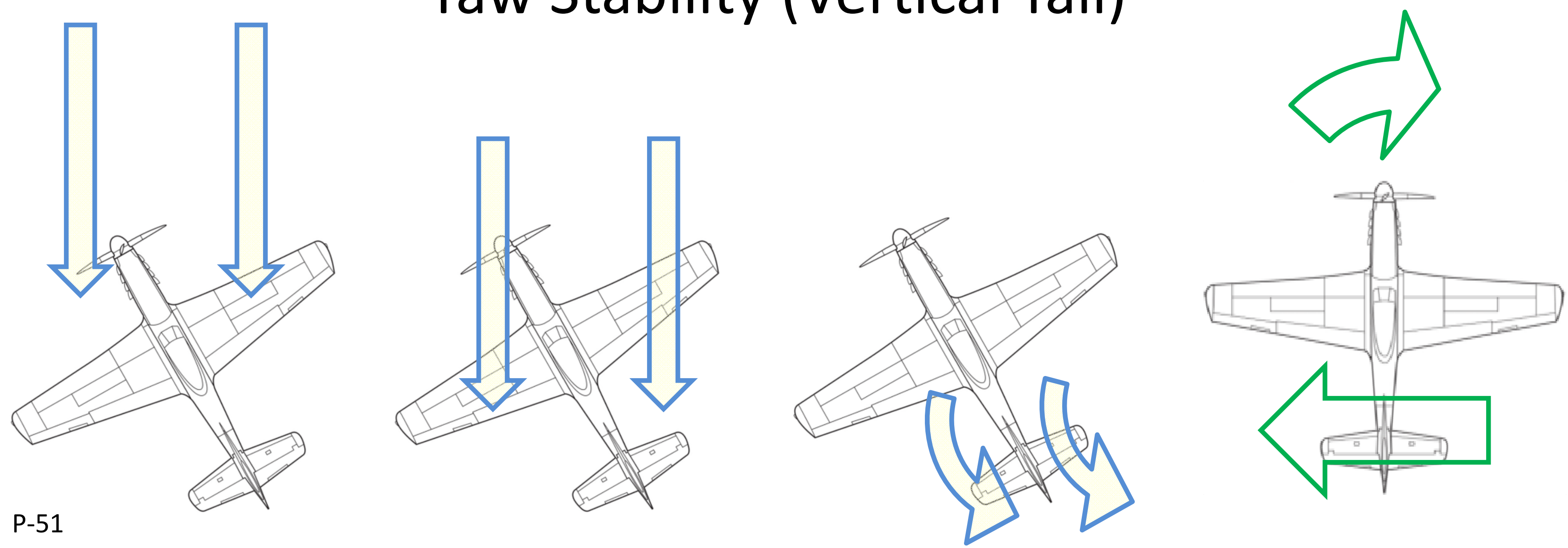




Stability

- Imagine a ball inside a bowl.
  - Push the ball away from the center of the bowl, up the wall, and let go: The ball will be pulled back towards the center. This is ***stability***.
- Imagine a pencil standing on its tip.
  - Push the pencil in any direction, and it will be pulled even farther in that direction, away from the center, and will fall over. This is ***instability***.
- To generalize: "Stability" means a system where a change generates an effect that tries to undo that change. "Instability" means a system where a change generates a force that makes the change happen even more quickly, creating the potential for a run-away/snow-ball effect.
- When it comes to airplanes, stability means that the airplane naturally wants to return to steady level flight, i.e. pointing the way it is going, with the wings level rather than banked, with no sideslip, at some desired angle of attack. A stable airplane naturally keeps flying in a straight line, even with no pilot inputs.

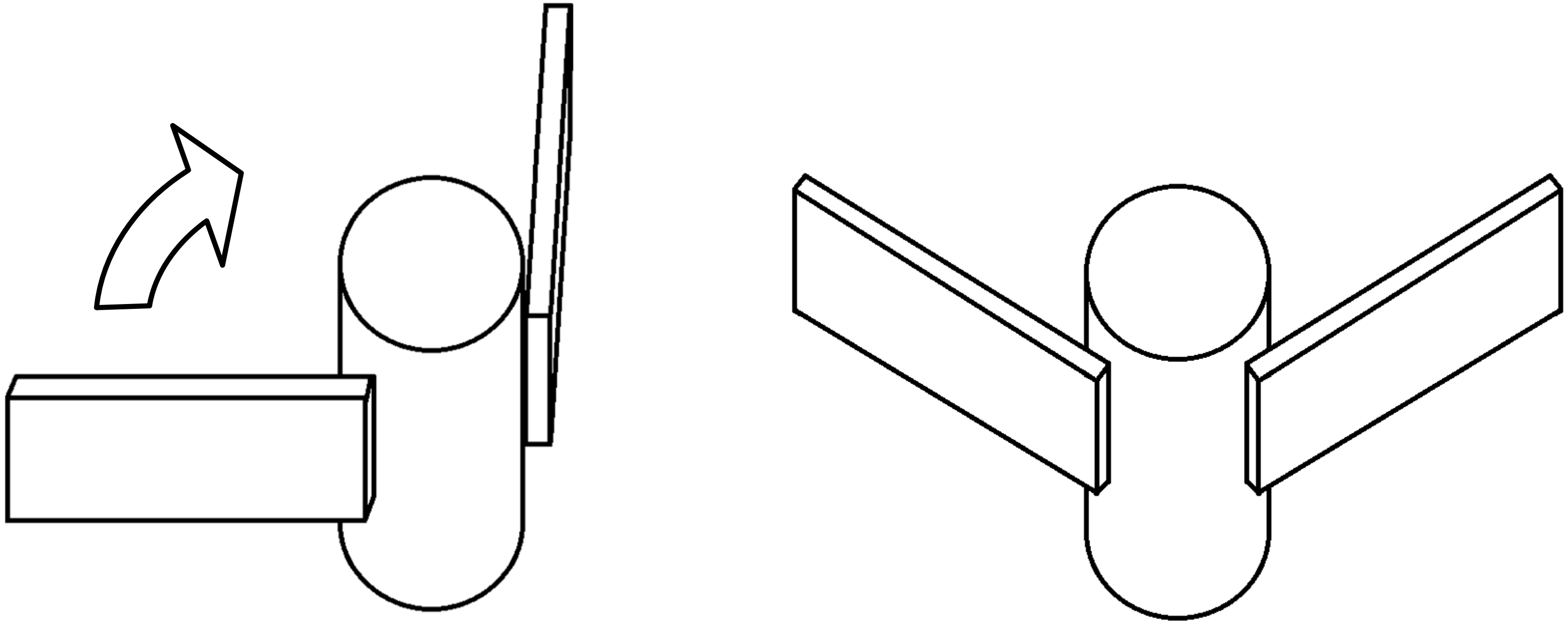
Yaw Stability (Vertical Tail)



Yaw Stability (Vertical Tail)

- [Here we will only discuss static stability. Dynamic stability is also very interesting, and very important to airplane design and performance, but a bit beyond the scope of this class. Research about things like phugoid modes, the Dutch roll, and yaw dampers, is left as an exercise to the student.]
- Let's start with yaw stability, because that's a simple one.
- Say that an airplane is flying at zero angle of sideslip.
- Due to a gust of wind or due to the pilot briefly kicking the rudder pedal, the airplane finds itself in a sideslip, i.e. pointing slightly to the side of the direction it's flying.
- The vertical fin will be at an angle that will deflect air in the direction away from where the airplane is pointing. This will push the tail towards the direction where the airplane is pointing, and swing the nose around, away from the direction it's pointing. This will "center" the airplane by a "weather vane" effect, i.e. force the airplane to point the way it's going.
- **In other words, the vertical stabilizer provides yaw stability.**
- **The same effect can be observed in arrows, shuttlecocks, etc.**

Roll Stability (Dihedral)



Imagine that these "airplanes" are "flying" out of the page.

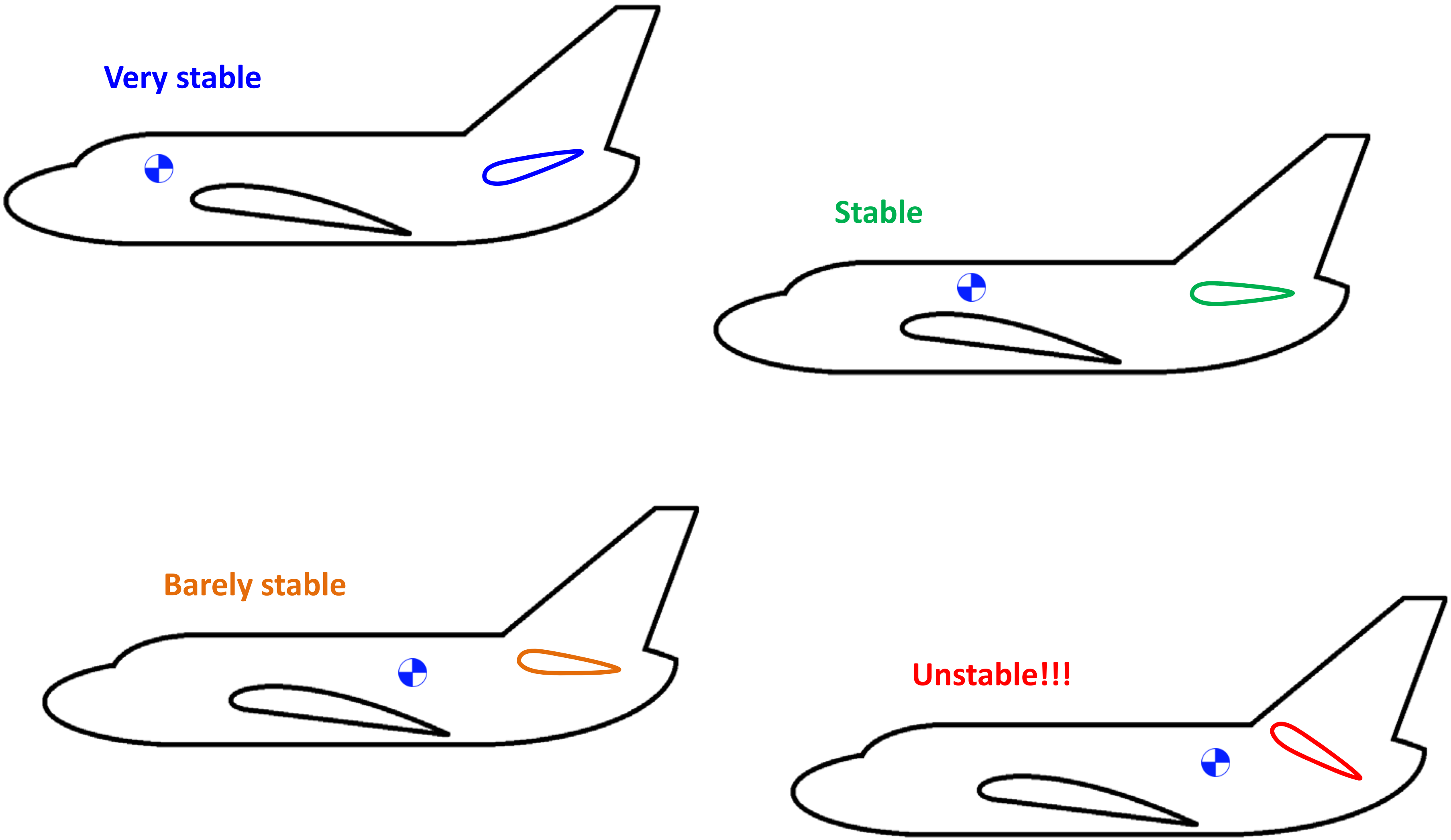
Due to higher lift on the lower wing (because the airplane is "sliding" towards that wing, sliding away from the upper wing), the "airplane" on the left will automatically roll until it is level like the one on the right.

Roll Stability (Dihedral)

- ***Dihedral*** provides roll stability. That's when the wings slope up away from the fuselage, i.e. the wingtips are higher off the ground than the wing roots.
- This may be hard to imagine in 3D, so grab a model of an airplane with dihedral wings if you have one handy, or just fold a rectangle of paper into a "V" and pretend that the fuselage is at the centerline (where the crease is).
- If an airplane with dihedral wings is at some angle of attack, then rolling in one direction will slightly increase the angle of attack of the "down" wing and slightly decrease the angle of attack of the "up" wing.
- This will make the "down" wing want to come back up, and the "up" wing want to fall back down.
- This is a very slight and gentle tendency (at low angles of attack and with slight dihedral) but enough to keep airplanes flying wings-level "on their own".

787 & Spitfire

Pitch stability (Decalage Rule)

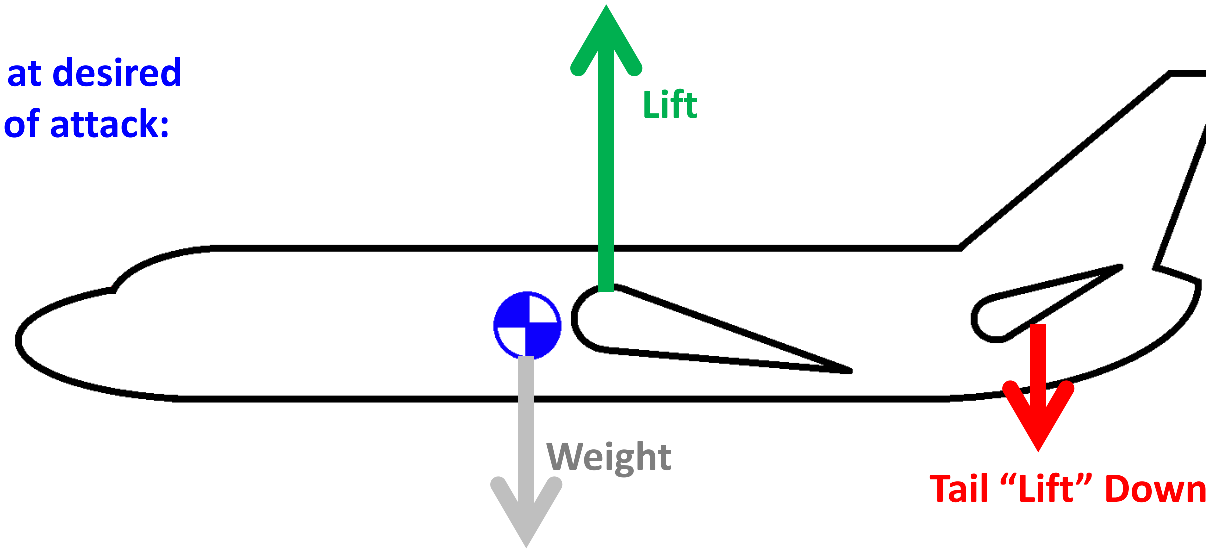


Pitch stability is ensured by the relative angle between the wings and the horizontal stabilizers. If that relative angle is "correct", then a change in angle of attack will cause the airplane to become slightly unbalanced, in a way that makes it want to naturally return to the desired angle of attack. How does that work? Let's think through four scenarios.

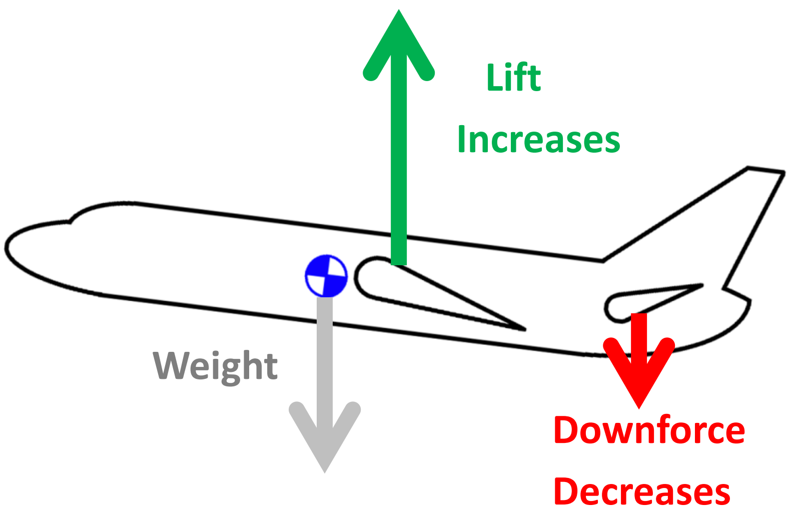
- **(1)**: Say that the wings are at 3° angle of attack, and the horizontal stabilizers are at -3°. So, for balance, the CG must be ahead of the wings. Therefore, upwards wing lift makes a nose-down pitching moment, and down-force on the horizontal tails makes a nose-up pitching moment. The airplane is balanced if those two moments cancel out. (We'll ignore the engines and other complications for now).
- Say that, due to pilot input or a bump of turbulence, the alpha increases by one degree. Now the wings are at 4° and the tails are at -2°.
- Wing lift (and thus nose-down moment) increases. Tail down-force (and thus nose-up moment) decreases. So now the airplane is slightly unbalanced: There is an overall nose-down moment from the wings. So the airplane wants to return to its "default" alpha.
- Or: Say that, due to pilot input or a bump of turbulence, the alpha decreases by one degree. Now the wings are at 2° and the tails are at -4°.
- Wing lift (and thus nose-down moment) decreases. Tail down-force (and thus nose-up moment) increases. So now the airplane is slightly unbalanced: There is an overall nose-up moment from the tails. So the airplane wants to return to its "default" alpha.
- Pitch stability: Positive!
- It's like the wings and the tail are "fighting": The wing wants to push the nose down, the tails want to push the nose up. If the angle of attack increases, the wings "win" temporarily and push the nose back down. If the angle of attack decreases, the tails "win" temporarily and push the nose back up.
- **(2)**: Say that the wings are at 3° angle of attack, and the horizontal stabilizers are at 0°. So, for balance, the CG must be right on top of the wings. Therefore, upwards wing lift makes no pitching moment, and the horizontal tails makes no pitching moment at the default angle of attack. The airplane is balanced if those two moments are all zero.
- Say that, due to pilot input or a bump of turbulence, the alpha increases by one degree. Now the wings are at 4° and the tails are at 1°.
- Wing lift increases (but still no moment, if right at the CG). The tails now make lift, and thus a nose-down moment. So now the airplane is slightly unbalanced: There is an overall nose-down moment from the tails. So the airplane wants to return to its "default" alpha.
- Or: Say that, due to pilot input or a bump of turbulence, the alpha decreases by one degree. Now the wings are at 2° and the tails are at -1°.
- Wing lift decreases (but still no moment, if right at the CG). The tails now make down-force, and thus a nose-up moment. So now the airplane is slightly unbalanced: There is an overall nose-up moment from the tails. So the airplane wants to return to its "default" alpha.
- Pitch stability: Positive!
- In this scenario , the horizontal stabilizers work just like the vertical stabilizer, or an arrow's tail feathers: They basically just want to stay at zero degrees angle of attack.
- **(3)**: Say that the wings are at 5° angle of attack, and the horizontal stabilizers are at 2°. So, for balance, the CG must be behind the wings. Therefore, upwards wing lift makes a nose-up pitching moment, and upwards lift on the tails makes a nose-down pitching moment. The airplane is balanced if those two moments cancel out.
- Say that, due to pilot input or a bump of turbulence, the alpha increases by one degree. Now the wings are at 6° and the tails are at 3°.
- Wing lift (and thus nose-up moment) increased by about 20%. But tail lift (and thus nose-down moment) increased by 50%! So now the airplane is slightly unbalanced: There is an overall nose-down moment from the tails. So the airplane wants to return to its "default" alpha.
- Or: Say that, due to pilot input or a bump of turbulence, the alpha decreases by one degree. Now the wings are at 5° and the tails are at 1°.
- Wing lift (and thus nose-up moment) decreased by about 20%. But tail lift (and thus nose-down moment) decreased by 50%. So now the airplane is slightly unbalanced: There is an overall nose-up moment from the wings. So the airplane wants to return to its "default" alpha.
- Pitch stability: Positive!
- As long as the wings are at a higher angle of attack than the tail, the amount of lift that they make is less sensitive to changes in angle of attack than the amount of lift that the tails make.
- **(4)**: Say that the wings are at 2° angle of attack, and the horizontal stabilizers are at 5°. So, for balance, the CG must be way behind the wings. Therefore, upwards wing lift makes a nose-up pitching moment, and upwards lift on the tails makes a nose-down pitching moment. The airplane is balanced if those two moments cancel out.
- Say that, due to pilot input or a bump of turbulence, the alpha increases by one degree. Now the wings are at 3° and the tails are at 6°.
- Tail lift (and thus nose-down moment) increased by 20%. But wing lift (and thus nose-up moment) increased by 50%! The airplane is unbalanced: There is an overall nose-up moment from the wings. So the airplane wants to increase its alpha even more… which will make this discrepancy (and its nose-up moment) even worse! Unless the pilot pushes the nose back down, the airplane will do a back-flip.
- Or: Say that, due to pilot input or a bump of turbulence, the alpha decreases by one degree. Now the wings are at 1° and the tails are at 4°.
- Tail lift (and thus nose-down moment) decreased by about 20%. But wing lift (and thus nose-up moment) decreased by 50%. The airplane is unbalanced: There is an overall nose-down moment from the tails. So the airplane wants to decrease its alpha even more… which will make this discrepancy (and its nose-down moment) even worse! Unless the pilot pulls the nose back up, the airplane will tumble forwards. If the wings are more sensitive to changes in alpha than the tail is, it's like the wings could easily be "blown back by the wind" and the airplane will want to swap ends.
- Pitch stability: Negative!
- Apparently, **the angle of attack of the horizontal stabilizer MUST be lower than the angle of attack of the wings!!!** This is the ***decalage rule.***

Why is the tail always pushing down?

Flying at desired angle of attack:

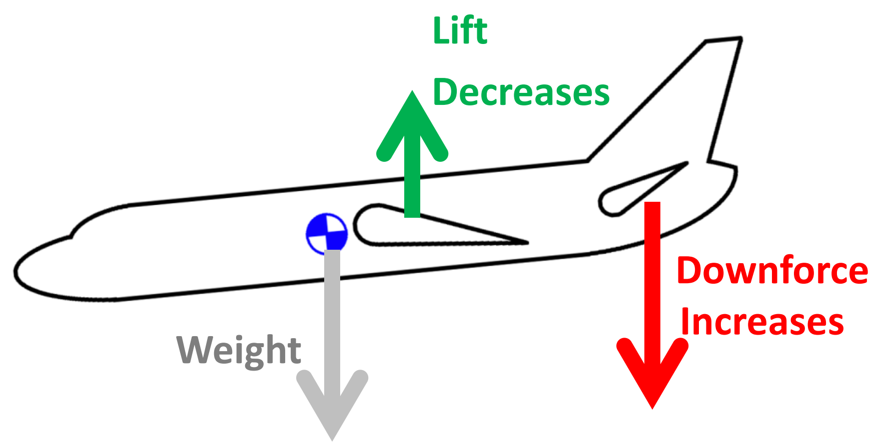


Increase in angle of attack?



Nose goes back down

Decrease in angle of attack?



Nose goes back up

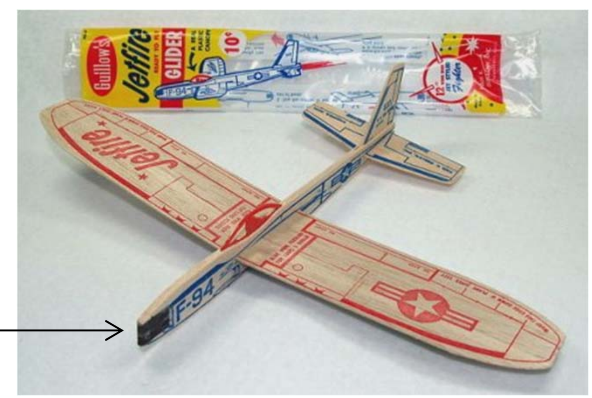
Why is the tail always pushing down?

- In most airplanes, the CG is ahead of the wing. This means the horizontal tail must push downwards for balance. In other words, lift from the wings generates a nose-down moment, and the tail down-force generates a nose-up moment. During cruise flight, they cancel out. But the wing and the tail are always "fighting", generating antagonistic (i.e. opposing) nose-up/nose-down moments.
- **If the angle of attack of the airplane goes up, the wings make more lift, but the tail fins make less down-force. The wings then start to "win" their "fight": Their now-larger nose-down moment overwhelms the tail fins' now-lower nose-up moment, and the nose wants to come back down.**
- **If the angle of attack of the airplane goes down, the wings make less lift, but the tail fins make more down-force. The tail fins then start to "win" their "fight": Their now-larger nose-up moment overwhelms the wings' now-lower nose-down moment, and the nose wants to come back up.**
- In other words: If the horizontal stabilizer tail fins are loaded downwards, then they are always "fighting" the wings when it comes to nose-up/nose-down moments. And if the tail fins are always fighting the wing, then any change in angle of attack will cause either the wings or the tail to momentarily "win the fight", and to move the nose back up or down until the default angle of attack is restored.
- [Note that, when trim is used, the "default" angle of attack changes. So while pilots often think of a trim setting as "balancing the airplane at a certain speed", what trim really does is make the airplane want to fly at a certain angle of attack. Same thing for the elevators: Pulling the yoke or joystick by a certain angle means telling the airplane: "Fly at this (higher) angle of attack!".]
- **But why do this? The tail down-force acts like "weight", subtracting from the payload and increasing induced drag. Why not have the tail at 0° or lifting just a little bit?**
- We have been ignoring the nose-up moment from the engines, and the fact that the pilot sometimes needs to command the nose to go down.
- For balance, the horizontal stabilizer needs to be at some angle during cruise. But **if engine power is added**, and if the engines are near the bottom of the fuselage, the engines make a nose-up moment. The tail needs to fight this moment, and thus get to a higher (or less negative) angle when engine power is increased.
- When **the pilot wants to command the nose to come down** (e.g. at the top of the climb-out and at the start of the descent to land), pushing forwards on the yoke/stick causes the elevators to deflect downwards. This increases the horizontal stabilizers' camber, and also effectively increases their angle of attack a little (because their trailing edges move downwards).
- In short: There are times when the angle of attack of the horizontal tail fins must increase (or become less negative) due to higher engine thrust, and there are times when the angle of attack of the horizontal tail fins must increase (or become less negative) due to maneuvering.
- During those times, the angle of attack of the horizontal tail fin must not exceed that of the wings! (Or the airplane will want to backflip/tumble).
- Therefore, during cruise, the angle of attack of the tail fins must be significantly lower than that of the wings, in order to provide some tail-fin alpha "margin" that gets less-than-totally used up if engine power is added and if the pilot needs to push the nose downwards.
- The end result: The horizontal stabilizers push downwards nearly all the time (so that, at the times when some nose-down moment is needed, this can be accomplished without the tail fins exceeding the angle of attack of the wings).
- For this reason, on the vast majority of airplanes, you want the CG to be ahead of the wings.

Keeping the CG forwards

RV-12

weight

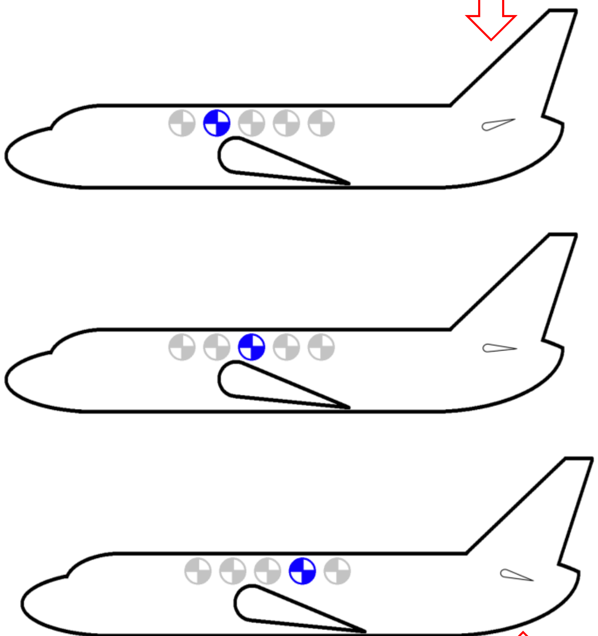


Keeping the CG forwards

- As we have seen, the further forward the CG is, the more downwards force (or the less upwards force, if the CG is behind the wing) is required from the horizontal stabilizer, for balance.
- As we have seen, the more downwards force the horizontal stabilizer makes relative to the wings, the more stable the airplane will be.
- Therefore, having a CG further forwards is good for stability.
- Most airplanes' CG is further forward than most people think:
  - Airliners' engines (the heaviest components) are not really "under the wings". Engine mounts protrude forwards and hold the engines mostly ahead of the wings.
  - On single-engine airplanes, the engines are all the way forwards in the nose. Not only that, but also: The engine mounts often hold the engines quite a bit ahead of the firewall.
  - If the engines go in the back, then the forward fuselage must be quite long (i.e. the wings must go relatively close to the back) in order for enough weight to be ahead of the wings (e.g. MD-80).
- However, there are disadvantages:
  - If the CG is too far forwards, the pilot would not be able to pull the nose up for takeoff!
  - The further forwards the CG is, the harder the horizontal stabilizer must push down, and the draggier it will be. Therefore, flying with the CG near the aft end of the allowable range will reduce drag (and thus increase fuel efficiency), and also reduce the stall speed and the takeoff and landing distances (because the tail will be making less down-force).

How big should the horizontal stabilizers be?

Small horizontal stabilizer: CG only a little forwards, and stabilizer angle of incidence has to be way down for balance. Might stall before wing! Airplane might not be able to rotate to take off!

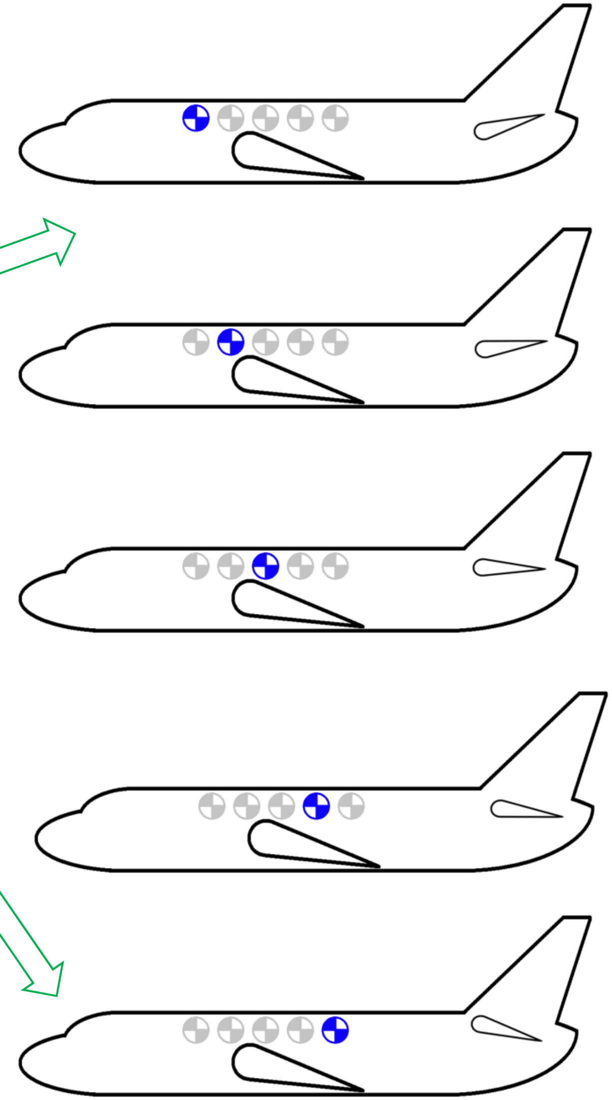


Small horizontal stabilizer: CG only a little aft, and stabilizer angle of incidence has to be way up for balance. Might violate decalage rule and make airplane unstable in pitch!

Large horizontal stabilizer: Deflection angle only changes slightly for balance as CG moves forward and aft.

CG can move further forward before angle of incidence of horizontal stabilizer gets so low it might stall before the wing.

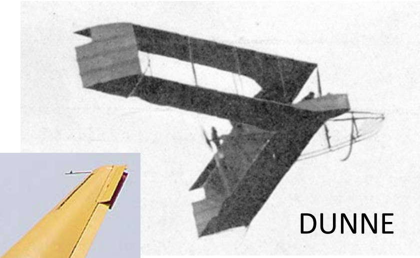
CG can move further aft before angle of incidence of horizontal stabilizer gets so high it might violate the decalage rule and make the airplane unstable.

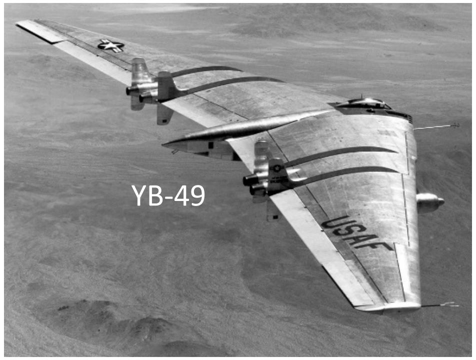


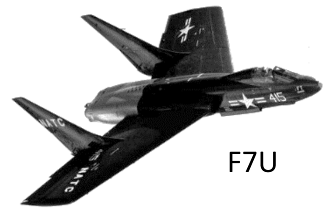
How big should the horizontal stabilizers be?

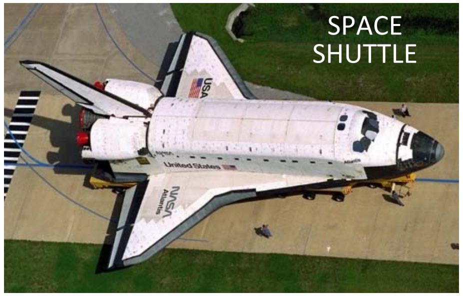
- All that we have learned so far is that the horizontal stabilizer needs to be at a lower angle of incidence than the wing, and that the combination of its size and location and angle of incidence has to provide balance for the Center of Gravity.
- So, now: Can you put the Center of Gravity near the center of lift of the wing and just have a tiny horizontal stabilizer?
- Yes, but: only if you ***know*** (or ***require***, from the people who own / operate / load the airplane) that the Center of Gravity will stay right there: Passengers must be seated in an evenly-distributed way, all fuel tanks must be close to the CG or used up in a balanced order (so that the CG does not shift much while fuel is burned), nothing too heavy must be put near the nose or tail without something heavy to counter-balance it at the other end, cargo can't be carried without first being weighed and put at the right spot.
- Owners and operators want some flexibility in loading their airplanes. They want to be able to put some cargo or a piece of equipment somewhere without having to weigh it or balance it with ballast in the nose or tail! They want to be able to carry freight that is heavy near the front or back. Throw some bags in at the last minute… In short, they need the CG to have an allowable ***range***.
- **The further back the CG is, the higher the angle of incidence of the horizontal stabilizers must be. So the aft end of the CG range is where the horizontal stabilizer would be just shy of the same angle of incidence as the wing** if the pilot were to command maximum elevator-down (nose-down)**. A bigger horizontal stabilizer would generate the same required moments at smaller angles of attack, so making the horizontal stabilizers bigger would extend the CG range further aft.**
- **The further forwards the CG is, the lower (more negative) the angle of incidence of the horizontal stabilizer must be. So the forwards end of the CG range is where the horizontal stabilizer is just shy of having an "equal and opposite" (i.e. upside down) angle of incidence as the wing. Why? Because, when the airplane slows down, you don't want the stabilizers to stall before the wing!** (This would effectively increase the minimum speed of the airplane)**. And if the angle of attack of the horizontal fins puts them on the verge of a stall, deflecting the elevator might stall them, and that would be bad too, e.g. during rotation as the airplane tries to take off, and during the flare as the airplane is about to touch down. A bigger horizontal stabilizer would generate the same nose-down moment at a less-negative angle of incidence, so making the horizontal stabilizers bigger would extend the CG range further forward.**
- The CG range is one of the competitive specs of an airplane, like range and fuel efficiency. **So the horizontal stabilizer is sized based on how much of a CG range your airplane needs in order to succeed in the market**. Would operators prefer an airplane with a narrow CG range but better fuel efficiency from a smaller tail? Douglas (MD-11) and Lancair thought so, but then… For an interesting analysis of their problems, see http://www.n91cz.net/Stability/Comparative_Stability_Study.pdf
- (In this class, we do not cover dynamic stability. Even if changes in pitch/roll/yaw try to return to zero, do they die down quickly or do they oscillate back and forth for a while first? Do oscillations in one axis cause disturbances in other axes? Could oscillations get more intense over time? E.g.: Look up Dutch rolls and the phugoid mode. The size, location, and angle of incidence of the tail fins impact this dynamic-stability behavior; They must be designed accordingly).
- Note: "Angle of incidence" is the angle of the wings or tail fins relative to the fuselage - unlike the angle of attack, which is relative to the airflow. In practice they are very close, but we say "angle of incidence" when asking "At what angle do we want to stick these components onto the sides of the fuselage?".

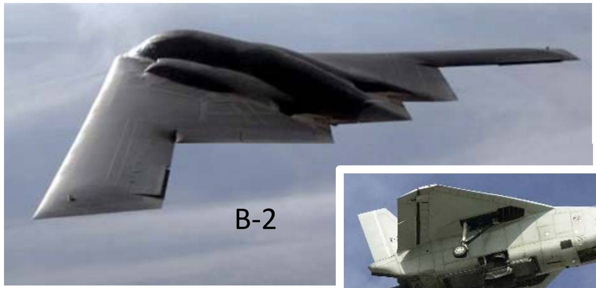
Blended Wing Bodies, Flying Wings, and Delta Wings











Some airplanes have no horizontal stabilizer at all! How do they get away with that?

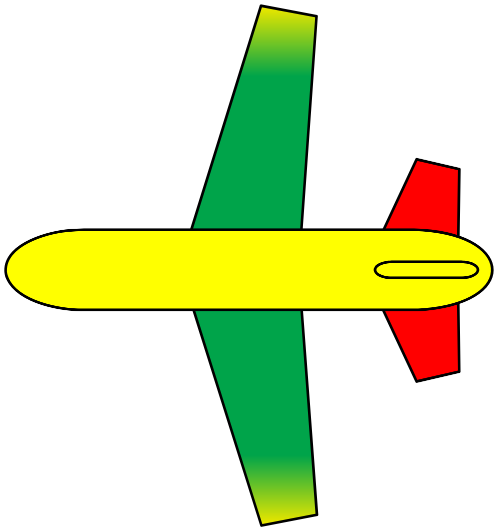
We'll explain why on the next slide. But first… Why would someone prefer a tail-less configuration? Pros and cons?

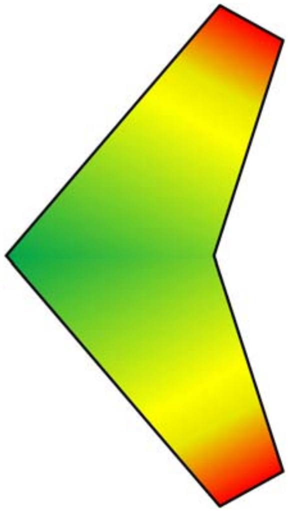
Tail-less airplanes are generally less draggy, because they eliminate the drag from the tail fins. Make the inside of the wing roomy enough, and you could even get rid of the fuselage! That would maximize the lift-to-drag ratio, the main measure of the aerodynamic efficiency of an airplane. People like Jack Northrop and the Horten brothers were obsessed with this idea.

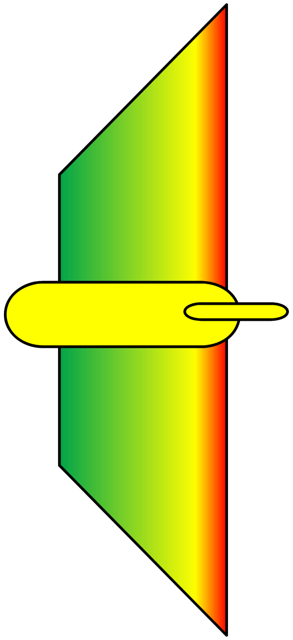
Many new UAVs (X-45, Phantom Eye, X-47B, PoleCat, RQ-170, ScanEagle, X-48, DarkStar, X-56, Taranis, Neuron) are flying-wing tail-less designs, primarily due to stealth. (One of the "Special Topics" presentations at the "Resources" page of UnderstandingAirplanes.com covers how flattened shapes reduce the radar reflectivity; by only reflecting radar [a] in fewer directions and [b] mostly away from the radar source). Many fighters (F-102, F-106, Draken, F4D, F7U, Mirage 3, Mirage 2000, Tejas, X-32) have delta wings due to lower wave drag at supersonic speed. But even for subsonic flight, "Blended-Wing Bodies" (BWBs) like the X-48 generate much less drag than an otherwise-equivalent "tube and wing" design.

- When people ask why the BWB / flying wing design is not used in airliners, the answers that typically come up are:
  - Harder to make derivatives. Can't just "stretch the tube" or "plug the wing";
    The manufacturer would have to redesign the whole thing with almost no parts commonality.
  - Very wide rows: Not 6 to 10 seats, more like 30+. Outboard seats would go way up and down whenever the airplane banks. Center seats would be unpleasantly far from the side-walls, in the middle of a "sea of people" like an auditorium.
  - No windows! Or maybe a few. In any case: Much less window area than an airliner.
  - Harder to evacuate in an emergency, especially if loading is through belly rather than through the leading edges.
    Similarly: Harder for airport service vehicles to service, especially if loading is through belly.
  - Dynamic stability will be poor. This can now be fixed with fly-by-wire systems (see slide 237), but it was a huge obstacle when Northrop made the YB-35 and YB-49 prototypes. The nose oscillated up and down slightly, making it impossible to aim the bomb-sight accurately. As mentioned earlier, even MD-11s and early-model Lancairs sometimes encounter dynamic-stability oscillations during the approach to land, due to their small horizontal stabilizers.
  - Tail-less airplanes stall in ways that are less predictable (e.g. at different alphas, depending on speed and weight, varying greatly with CG location) and often less stable than conventional airplanes. Their spin entry is not fully understood, and spin recovery techniques are sometimes the opposite of those for a conventional airplane. Here is a video of a Northrop test pilot talking about (1) the N9M fatal crash due to a spin, (2) the YB-49 fatal crash during stall testing, from which Edwards AFB got its name, (3) what happened when they tried the same thing in the B-2 decades later. (Note: One of the main objectives of the recent X-48 program was to gather data about how flying wings stall and spin, so that if one is ever certified for commercial service, we will be able to make sure that it stalls and spins predictably, manageably, and recoverably).
    (1: https://www.youtube.com/watch?v=Xax4q4Ctdh0#t=963 2: https://www.youtube.com/watch?v=Xax4q4Ctdh0#t=1805 3: https://www.youtube.com/watch?v=Xax4q4Ctdh0#t=2588)
- But the main drawback is: **The lack of a tail means that the CG range is extremely narrow**. We just covered how, the bigger the tail, the more places where the CG can be without the airplane being unbalanced or unstable. But with zero tail? You can only put the CG at one spot! (…or, rather, within a narrow range, thanks to the mechanisms we will cover in the next slide). That's ok if all you'll carry is bombs (attached to a specific spot every time) and fuel (in tanks that can be emptied in the desired order). But cargo pallets, passengers, luggage? They are much less predictable and require a wider CG range (unless you weigh each passenger and assign seats accordingly).

Blended Wing Bodies, Flying Wings, and Delta Wings



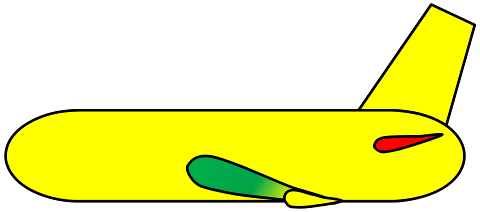


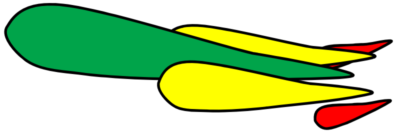


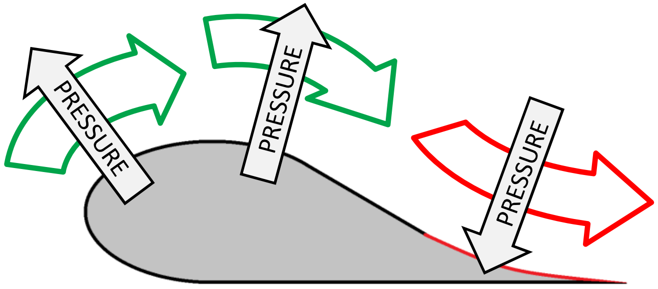
normal airplane

swept and twisted flying wing

tail-less design with reflex camber







(exaggerated curvature)

How do flying wings, delta wings, and Blended Wing Bodies have a CG range at all,rather than requiring the CG to be at one specific spot (right at the center of lift)? There are two ways, both of which allow you to put the center of gravity near the front, so the wing acts as a stabilizer:

(1) If the wings are swept, then the tips are further aft. If the wings have twist/wash-out, then **the tips are set at a lower angle of incidence than the rest of the wing, thus acting like a horizontal stabilizer**.
This is why nearly all tail-less flying wings are swept, even very slow ones like hang-gliders. And…

XM-1

(2) Flying-wing airfoils can provide some nose-up moment. This allows the CG to be ahead of the center of lift, so the whole wing acts as a stabilizer. This is accomplished by "**reflex camber**": The upper surface of the wing is slightly concave along the trailing edge. Air approaches the trailing edge at a relatively steep downwards angle, but then gets pushed slightly upwards at the last second, and goes over the trailing edge at a *less-steep* downwards angle. That last-minute deflection pushes the trailing edge downwards. **This can be thought of as simply attaching the horizontal stabilizer – a surface at a lower angle of incidence than the main wing – to the trailing edge of the wing.**

With enough reflex camber, it is possible to have a straight flying wing, with no sweep! Charles Fauvel specialized in these, starting in France in the 1930s and culminating in the AV-60. The Dyke Delta and NASA's solar-powered Pathfinder and Helios are some other classic examples. Most striking are the "Flying Planks" made by Markse [e.g. XM-1] and Backstrom [e.g. EPB-1] and Winton [e.g. Facet Opal], which, as their nickname suggests, consist of a single large rectangular wing with a small fuselage in the middle. The Lockheed DarkStar UAV also applied this concept, but the first prototype crashed due to instability. For more examples, see http://www.nurflugel.com/Nurflugel/Fauvel/e_autres.htm

DarkStar

EPB-1

In any case: The CG range will be narrow when compared with a normal airplane whose aft-most surfaces are much farther back (and thus are able to generate greater nose-up moments with less down-force).

The previous slide shows a conventional airplane, a twisted swept flying wing with a conventional airfoil, and a flying wing whose airfoil has reflex camber. In all diagrams, colors roughly correspond to the angle of incidence: Positive angles are green, with yellow indicating a neutral (horizontal) or small angle of incidence, and red meaning a very small or even negative (downwards) angle.

Facet Opal

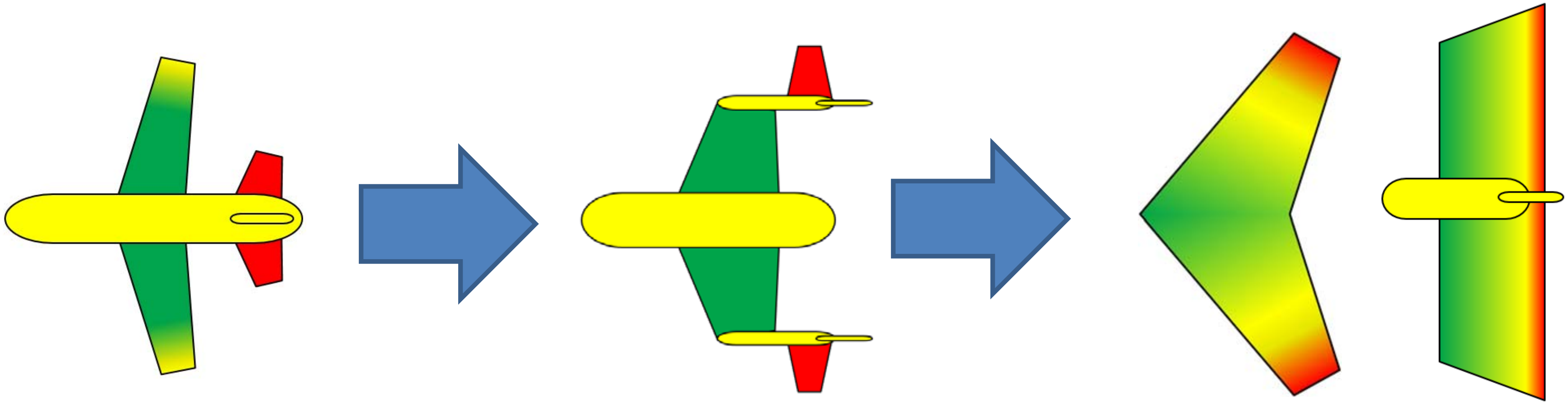
Tail-less stability through reflex camber and sweep+twist

Dyke Delta

X-47B

These photos clearly show the reflex camber on the Dyke Delta (notice how the trailing edge is less steep, closer to horizontal, than the upper wing skin just ahead of it) and the wing twist on hang gliders and on the X-47B (notice how the tips are angled downwards, relative to the centerline which is at an upwards angle of attack).

Interestingly, the SpaceShipOne design can be thought of as an intermediary between a conventional airplane and a flying wing. Its horizontal stabilizers are mounted on booms that come aft from the wingtips:



Quasi-BWBs / Hybrid Wing Bodies

BOEING/NASA X-48C

BOEING "SPEED AGILE"

LOCKHEED "SPEED AGILE" 1

LOCKHEED "SPEED AGILE" 2

BOEING/NASA
FUTURE TRANSPORT CONCEPT

LOCKHEED HWB

Quasi-BWBs / Hybrid Wing Bodies

- Many of the latest designs that implement BWB principles actually include a small set of horizontal stabilizers or a V-tail at the back of the aircraft, connected by a small tail boom. (This is interestingly similar to Jack Northrop's first airplane in 1929…)
- This may be the only way to get most of the benefits of a BWB (including stealth, which the military likes, as well as lower drag, less intense load concentrations at the side-of-body, etc.) if the stall-spin behavior must be predictable and manageable and recoverable (i.e. not dangerous).
- In other words, the only way to get a BWB to stall like a normal airplane might be to give it tail fins, at least small ones.
- In any case, this certainly expands the CG range, i.e. the freedom to carry payload that is heavy near the front or near the back.
- Lockheed has published a proposal for a C-17 replacement that they could develop in ~10 years. They claim their HWB would use 70% less fuel than the C-17. While this may or may not be an apples-to-apples comparison (i.e. Does it have a bigger wingspan than the C-17? Does it have the same rough-field takeoff and landing capabilities?), even if it is exaggerated (maybe it's "only" 40% less fuel), it is clearly a much more fuel-efficient, lower-drag design.
- For more details (structures, drag reduction, propulsion…) see http://arc.aiaa.org/doi/pdf/10.2514/6.2013-1097
http://arc.aiaa.org/doi/pdf/10.2514/6.2014-1285

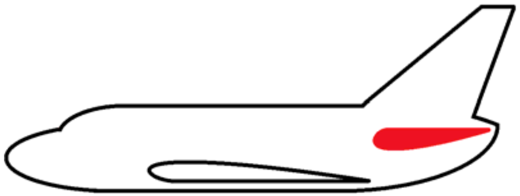
Fly By Wire & Artificial Stability

F-16

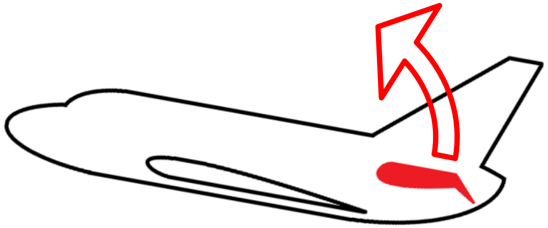
YF-22

A320

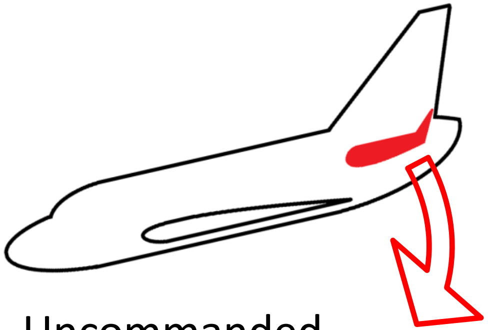
Shuttle



Just flying along…



Uncommanded increase in alpha?
Elevator goes down to bring tail back up.



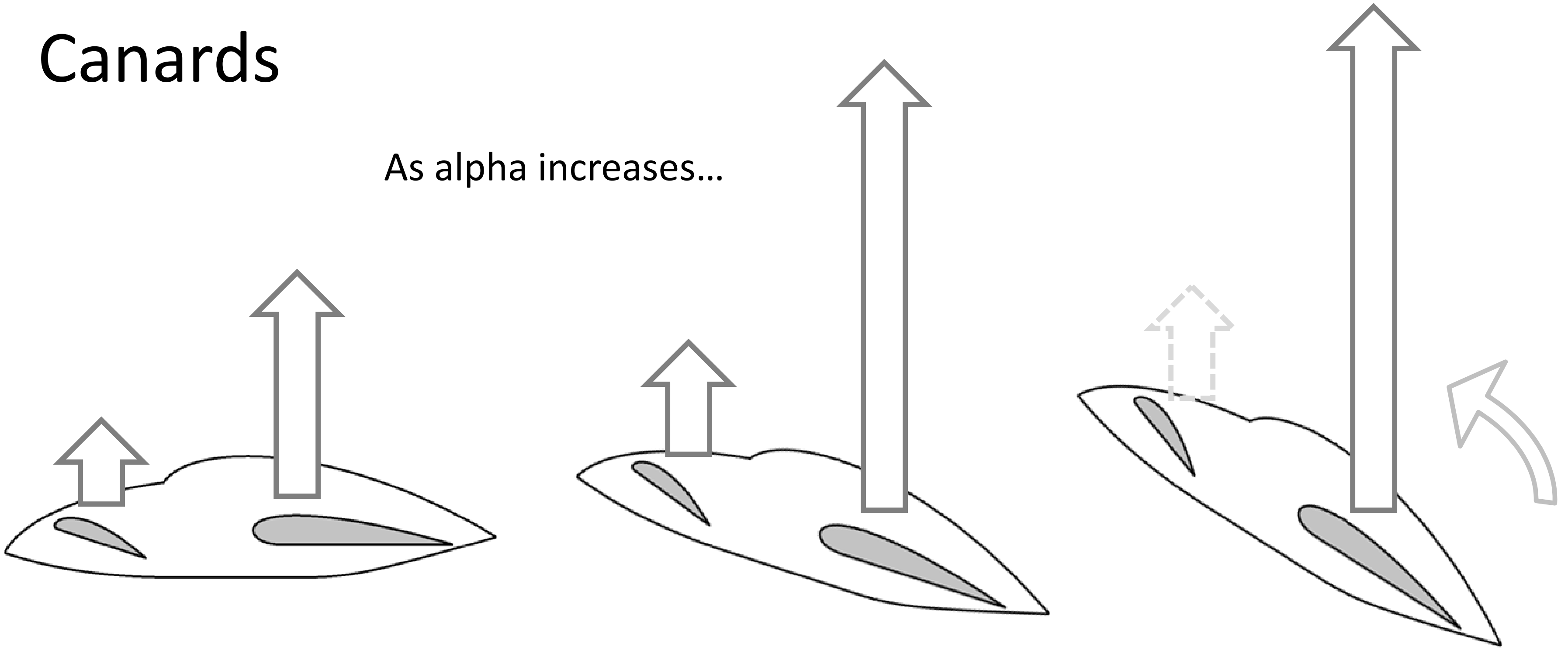
Uncommanded decrease in alpha?
Elevator goes up to bring tail back down.

Fly By Wire

- The term "fly by wire" has many connotations.
- Strictly, all that it means is that the control surfaces are moved by electrically-powered actuators, or by hydraulic actuators controlled by an electric signal, instead of a mechanical (push-rod, cable, or hydraulic) connection from the cockpit controls to the control surfaces. (By this definition, every remote-control airplane has fly-by-wire).
- Typically, there is a computer in the loop that "interprets" the pilot's input, and commands the control surfaces by sending signals that are non-linear or that change as a function of alpha and/or dynamic pressure (e.g. pilot inputs cause larger deflection at slower speeds).
- In some airplanes – infamously, in Airbus airplanes more so than Boeing airplanes – fly-by-wire systems have ***envelope protection***. This means the computer does not want the airplane to enter certain regions of the flight envelope (e.g. pitch down more than 15 degrees, pull more than 2.5 Gs). In some airplanes (Airbus), a pilot's command to bank further or pull up harder would not result in control surface deflections into those regions, i.e. the computer simply ignores the pilot. In other airplanes (Boeing), the controls become stiffer, they might shake, aural warnings might sound… i.e. the airplane still enters the "undesired" region of the envelope, but under clear protest.
- Some of the first implementations of fly-by-wire in the 1970s (F-16, Space Shuttle) implemented ***artificial stability***. (The Blackbird had a hydraulic version of this). This means that the computer would send commands to the elevator based not only on pilot inputs but also on the alpha sensor reading: An uncommanded increase in alpha causes the elevator to deflect downwards and push the tai up, mimicking the force from a bigger stabilizer… and an uncommanded decrease in alpha causes the elevator to deflect upwards and push the tai down, again mimicking the force from a bigger stabilizer. **This way, smaller tail fins can be used, because these elevator deflections mimic the "lift as a function of alpha" characteristics of a larger tail. Drag is reduced but stability is preserved.**
  - One problem: Perfecting the "gains", i.e. just how much the elevator should deflect as a function of alpha (and as a function of how alpha is changing, i.e. of whether the airplane is returning to the desired alpha or moving away from it). Excessively high gains can lead to oscillations. These have caused bouncy Space Shuttle landings and the crashes of fighter prototypes (Gripen and YF-22).
  - Another problem: The smaller tail fin is capable of a maximum force that is smaller than if the tail were larger. So at some alpha, the tail can no longer fight the instability, and the airplane tumbles end-over-end. This is not a problem if high alphas can be avoided… But as the Space Shuttle Columbia accident showed, sometimes you really need a bigger tail in order to keep the aircraft pointed the way it is going.

Canards

As alpha increases…



- Some (relatively few) airplanes have canards instead of horizontal stabilizers.
- Canards are set at a higher angle of incidence than the wing, for balance and stability. So…
  - **Decalage rule is met**: Any increase in angle of attack causes a small increase in the lift of the canard but a big increase in the lift of the wings, so the wings push tail back up: Wings act as stabilizer!
  - **The airplane never really stalls**. The canard stalls first, and if it does, the wing is still generating most of the lift required for flight, and the nose gently comes down until the canard un-stalls.
  - **The airplane cruises more efficiently than an airplane with a horizontal stabilizer**: A stabilizer pushes down, making the airplane "heavier", lowering the useful load. A canard ***helps*** the wing, rather than fighting it.
- Why don't more airplanes use canards? **Canards need more runway**. The canard stall speed is faster than the wing stall speed. This faster stall speed (rather than the wing stall speed) now becomes the airplane's minimum speed. The approach speed is a multiple of this minimum speed (usually ~115%). So, all other things (i.e. airplane weight and wing size) being equal, a canard airplane takes off and lands faster than a conventional airplane.
- Adding flaps, slats, etc., is not usually an option: Flaps would be at the very back of the airplane, and would require an even larger upwards force from the canards for balance – and the canard is already on the verge of stalling. The canard flies at a higher alpha than the wing, so in order to not stall at slower speeds, it will need ***more*** high-lift devices than the wing (e.g. vortex generators). Additionally, the elevator is on the canard, making it harder to add flaps and slats to the canard, thus making it very hard to add flaps and slats to the wing. (A conventional horizontal stabilizer is at a lower angle of attack than the wing, so it's far from stalling. Just trimming it downwards and/or deflecting the elevator upwards a little provides enough force to balance the airplane, especially since on a conventional airplane, the flaps and slats are not too far behind the CG).
- The fact that the canard airplane is "lighter" (no down-force from the tail) mitigates these landing-speed problems somewhat, but does not totally eliminate them. Making the wings and canards a little bigger would help, but the added weight and drag are comparable to just having a horizontal tail in the first place.
- So canards generally aren't used by airliners (which already need lots of runway) or by bushplanes (which minimize take-off and landing distances) or by trainers (Landing slowly is easier and safer). Canards can be found on European jet fighters (Typhoon, Rafale, Viggen, Gripen…), on some X-planes (X-29, X-31, X-36…), on the occasional high-speed airplane (XB-70, Tu-144), and on small airplanes (VariEze, Long EZ, Quickie, Cozy, Defiant, Velocity, Berkut…) designed for people who like to travel in their own airplanes, who can't afford a business jet, who want high speed and good fuel efficiency, and who do not mind only being able to use airports that have relatively long paved runways.

T-tails, High Wings, and Tail-Mounted Engines

HIGH WINGS

PROS

- Less susceptible to FOD damage
- Belly & floor can be very low to ground
- Allows higher-diameter (more efficient) engines e.g. big propellers
- Engines at almost the same height as CG: Changes in power do not require changes in pitch trim; easier to fly
- Flaps can be steeper: Good for STOL

CONS

- Harder to meet ditching requirements
- Landing gear needs pods on sides of lower fuselage (adding drag) or on wings (requiring tall, heavy gear)
- Engines at same height as CG: Thrust does not provide nose-up moment. Horizontal stabilizer must work harder during cruise to balance the airplane than it would if engines were lower
- Engines and wings are slightly less easily serviceable
- Center wing box protrudes into cabin more than low wings (because the fuselage crown above the ceiling is less tall than the cargo bay below the floor)

Military likes high wings due to low fuselage (can be loaded and unloaded without service vehicles) and lower FOD risk (for operations on unimproved runways). Regional airlines like high wings because propellers can be larger-diameter, more efficient.

TAIL-MOUNTED ENGINES

PROS

- Many of the advantages of high wings, without most of the cons: Slightly less susceptible to FOD damage, belly can be very low to ground, higher-diameter engines possible, and engines at same height as CG so changes in power do not require changes in pitch trim.
- Low wings + low fuselage belly = landing gear can be extremely small, lightweight, and strong
- Engines closer together: Rudder can be smaller.
- Wings can be "clean": simpler and better
- Center wing box crosses fuselage close to the aft end. In narrow-fuselage airplanes such as business jets, wing structure is "out of the way" of the cabin, e.g. under aft cabin wall.
- Quieter cabin, all other things being equal. (But "all other things" are rarely equal: Airplanes with tail-mounted engines tend to use loud engines!)
- Engines provide "free" horizontal stabilizer area, i.e. horizontal stabilizers can be slightly smaller. However…

CONS

- … Aft fuselage is more dense, so distance from wings to tail must be smaller (i.e. CG and wings are further back), so horizontal stabilizers must be slightly larger
- Engines at same height as CG: Thrust does not provide nose-up moment. Horizontal stabilizer must work harder (i.e. must be draggier) during cruise to balance the airplane than if engines were lower
- Engines are slightly less easily serviceable

Business jets like tail-mounted engines. Fuselage is narrow, not much space under floor. Putting the wing structure at the aft end of the cabin means no "bump" on the floor, and is at natural location for a lavatory and/or a cargo compartment bulkhead.

"T" TAILS

PROS

- Horizontal stabilizers and elevators not in fuselage wake, are exposed to faster "fresh" air, can be smaller and more effective.
- Horizontal stabilizers and elevators can be slightly further aft (because vertical stabilizer is swept), can be smaller and more effective.
- Tail cone does not need flattened sides: Cheaper, lighter, less draggy.

CONS

- Possibility of deep stall: At high angles of attack, horizontal stabilizers might go into wake of stalled wings, losing effectiveness and making stall unrecoverable. (Infamous BAC111 accident in 1963. A400M prototypes had downwards-firing rocket engine in tail cone in case this happened).
- Vertical stabilizer must be stronger, ends up being heavier
- Vertical stabilizer tends to be wider (thicker) for strength: more draggy
- Airplane slightly less easily serviceable: Harder to fit through (under) some hangar doors

T tails are typically used to prevent the engine exhaust from hitting the horizontal stabilizers in airplanes with high wings or tail-mounted engines. Exceptions exist (e.g. some Piper Arrows have T tails; the B-52 & An-124 don't).

High Engines

BERIEV Be-200

SHORT SUNDERLAND

ANTONOV AN-72 / 74

PIPER JET

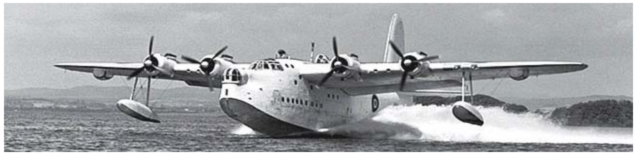
YC-14

LAKE LA-4

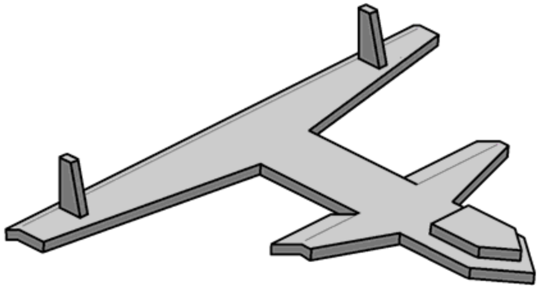
SEAWIND

HONDAJET

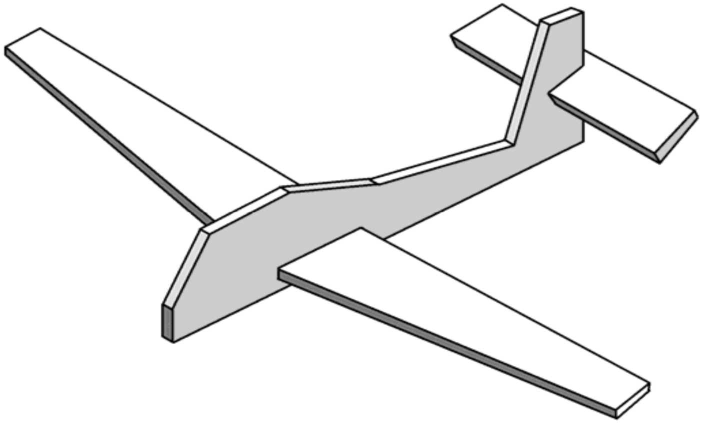
High Engines



- Placing an engine on the vertical stabilizer, on top of the wings, etc., requires some kind of heavy structure e.g. an engine pylon. Then again, placing an engine in more conventional places – on the nose, under the wings, on the sides of the tail cone – also requires heavy engine mounts / pylons. So high engine placement is not necessarily heavier.
- Nearly all single-engine jets are fighters/trainers with the engine in the fuselage. The very few single-engine transport jets (i.e. which need the fuselage volume to carry people and things) place their engine at the very back and/or top of the fuselage, e.g. Stratos 714, PiperJet, Cirrus Vision, Epic Victory, Excel SportJet.
- Seaplanes, of course, benefit from having their engines placed high off the water, with plenty of clearance.
- Other airplanes – e.g. Antonov 72 & 74, Boeing YC-14 – use high engines to minimize FOD issues.
- The main problem with high engines is the thrust above the CG. This means two things:
  - During takeoff climb, and cruise, the engine thrust creates a nose-down moment, which must be balanced by a nose-up moment from the horizontal stabilizers. (The alternative would be an aft CG location, which is bad for pitch stability as we have seen). So the horizontal stabilizers must be working harder – i.e. must be draggier – during cruise than they would if the engines were lower. Low engines help the horizontal stabilizers fight the nose-down moment from the wings, while high engines create a nose-down moment themselves (in addition to the one from the wings) which forces the horizontal stabilizers to have to “fight harder”.
  - If the airplane is trimmed (balanced), reducing power (e.g. just before landing) will cause the nose to go up (because the engine thrust will no longer be canceling out the nose-up moment from the horizontal stabilizers). The pilot must reduce power and push the stick forward (or re-trim the airplane) at the same time. This is not so bad at the start of the descent, where it can be done gradually and the worst case is the airplane climbing and slowing down a little. However, at the flare that happens when the airplane is about to touch down, a non-compensated nose-up movement could cause a stall and a crash. A pilot landing a seaplane must keep a very careful eye on the nose-up angle and keep it from going up (by pushing forward on the controls) when the power is reduced.



Gliders Activity

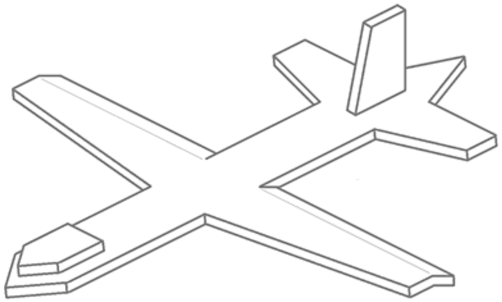


The challenge:

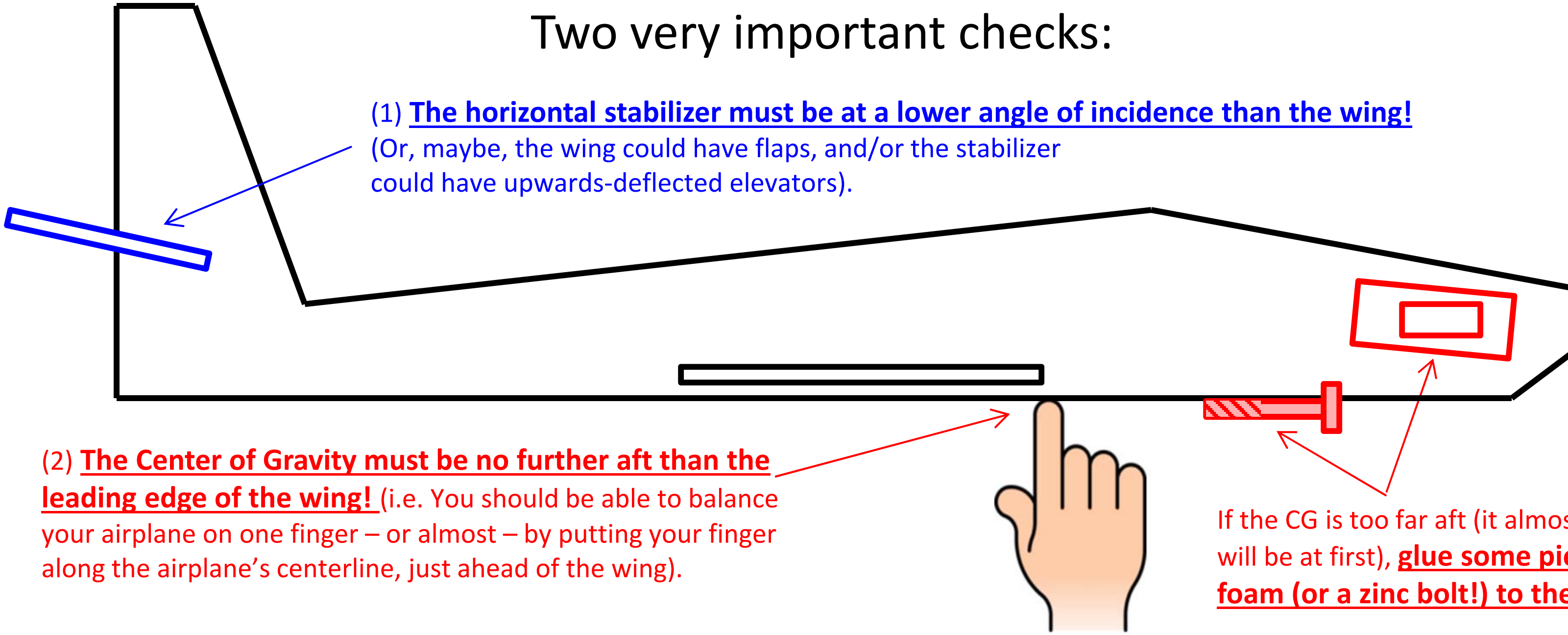
- Design and build a ***BALANCED*** and ***STABLE*** glider!
(i.e. one that flies in a straight line when thrown)

Remember:

- Pitch stability comes from the decalage rule: Flat surfaces further aft must be at lower angles of incidence than flat surfaces further forward.
- Balance means getting the CG in the right place (typically towards the front).
- Roll stability comes from wing dihedral.
- Yaw stability comes from the vertical stabilizer near the back (and is hurt by any vertical surface near the front, e.g. a “747 hump”).
- Say you throw your glider and it noses up. Is the CG too far aft, or is your glider unstable in pitch? (How do you tell? Then what do you do?)



Two very important checks:

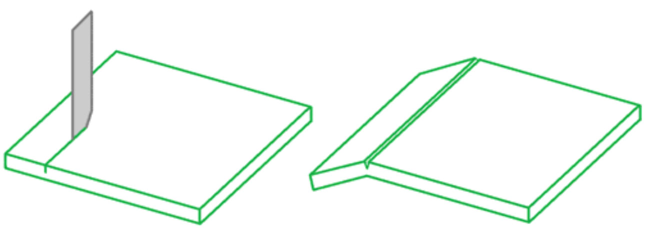


(1) **The horizontal stabilizer must be at a lower angle of incidence than the wing!** (Or, maybe, the wing could have flaps, and/or the stabilizer could have upwards-deflected elevators).

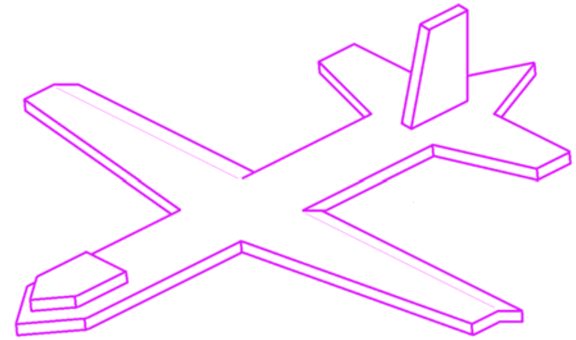
(2) **The Center of Gravity must be no further aft than the leading edge of the wing!** (i.e. You should be able to balance your airplane on one finger – or almost – by putting your finger along the airplane's centerline, just ahead of the wing).

If the CG is too far aft (it almost certainly will be at first), **glue some pieces of foam (or a zinc bolt!) to the nose.**

Handy tips:



When you throw your glider, **throw it at a slight downwards angle, and not too fast**. In other words, try to aim for the terminal glide angle and speed, rather than a ballistic flight-path!



To make trailing-edge flaps, make a shallow cut on the upper surface of the foam, cutting only the upper-side paper but not the lower-side paper, parallel[*] to the trailing edge and an inch or two ahead of it… then bend the trailing edge downwards. (To make elevators, cut only the lower surface of the horizontal stabilizers, and then bend up). [*] Not necessarily parallel: You may wish to make the flaps take up more of the chord (i.e. make them bigger) in the inboard region, and taper (become narrower) as you cut outboard, by cutting diagonally and making the cut get closer to the trailing edge near the wingtips. This will give some twist to the wing!

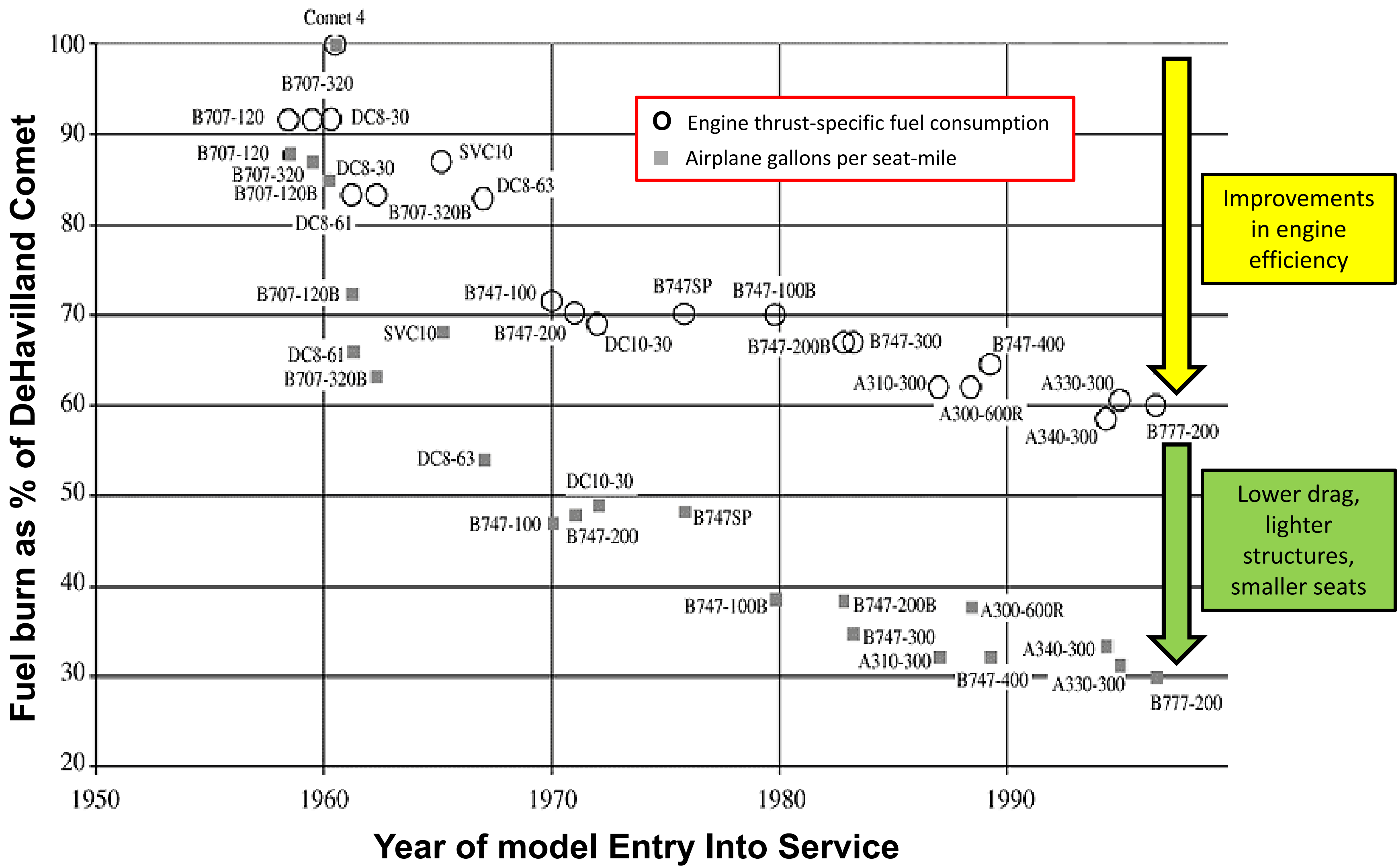
Your airplane will have stronger structure and fewer parts if you cut out the entire airplane planform ("top view") from the sheet of foam in one piece. Then all you have to do is add a vertical fin (and/or winglets if you wish), bend the horizontal stabilizers downwards (or just add an elevator to their trailing edges and deflect it upwards, and/or add flaps to the wings), and get the CG in the right place by adding weight to the nose.

Thrust and Engines

Thrust and Engines

- **Propeller engines** (piston and turboprop) have great historic importance and are still used in many modern airplanes. However, they will not be covered in-depth in this jetliner-oriented version of the course. We will only discuss the limitations of propeller engines, in order to explain the advantages of jet engines.
- **Jet engines** are used in most high-performance airplanes. High bypass engines are used in large transports, low bypass engines are used in fighters (Turboshaft engines used in helicopters, and turboprop engines used in small transports, also have jet engines at their core).
- **Exotic engines** will also not be discussed in depth. However, the main operating principles behind ramjets and electric/solar power, and their advantages and disadvantages, will be briefly explained.

Fuel Efficiency



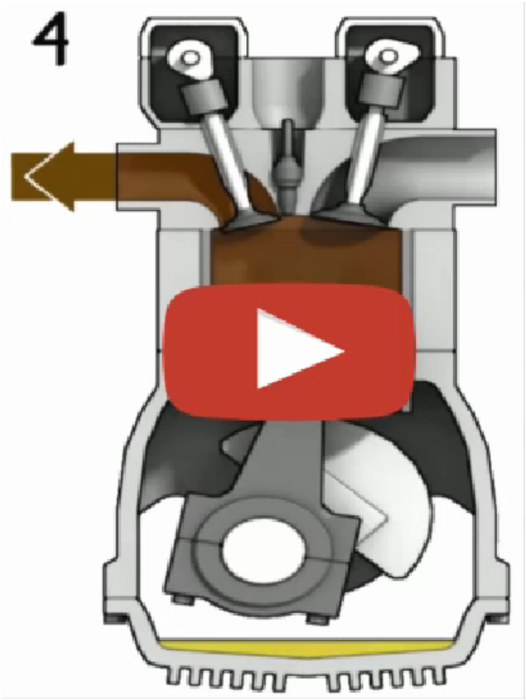
Fuel Efficiency

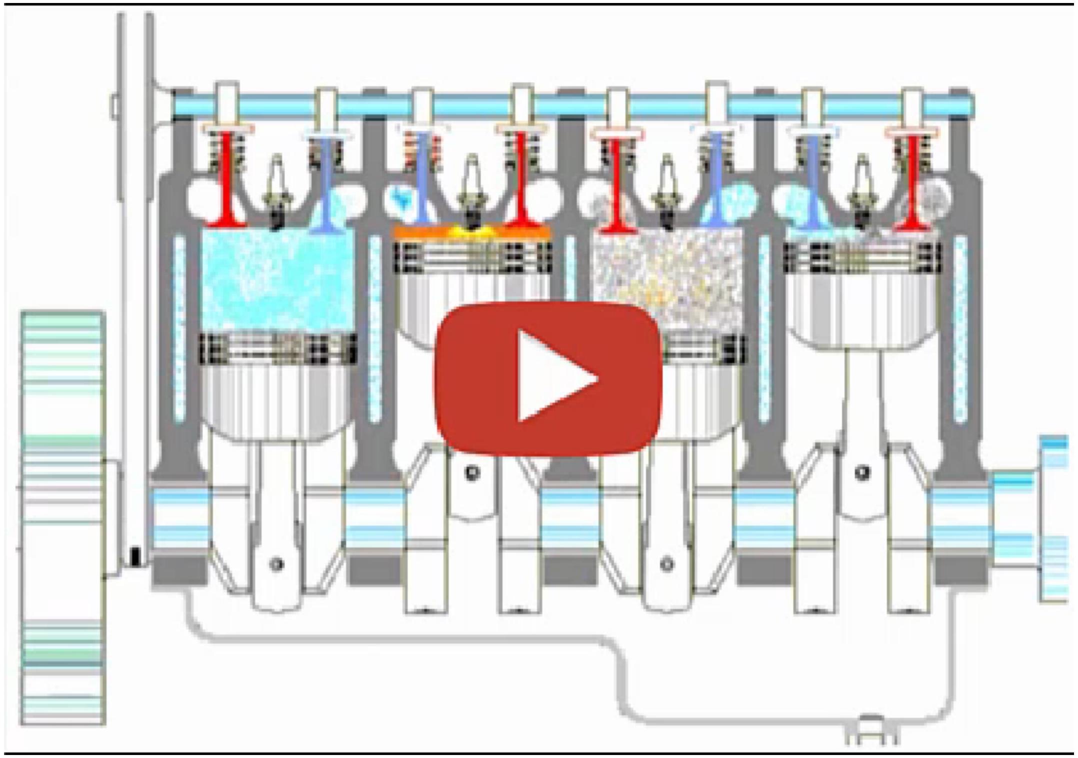
- A very large fraction of the costs that go into operating each flight are the cost of fuel.
- Therefore, as you know, airlines want airplanes that are as fuel-efficient as possible.
- A more fuel-efficient airplane means lower operating costs, higher profits, and more competitive ticket prices.
- We have discussed some ways to reduce fuel burn (i.e. lowering drag) and we will discuss some more (e.g. reducing structural weight, among others[*]). But the single most important way to reduce fuel burn is to make engines more efficient.
- [*: Passengers will pretty much always buy the cheapest ticket. Another way to reduce the fuel burn per passenger is to make smaller seats (e.g. less leg-room) so that more passengers share the cost of each flight. People complain about smaller seats… but they still buy the cheapest tickets, even if it's with the airline that has the smallest seats!]
- Airlines did not always compete on fuel burn. For decades they competed on speed, range, and comfort/luxury. But the introduction of high-bypass turbofan engines allowed for a significant reduction in fuel burn, and thus, in ticket costs… which caused huge growth in the air-travel market, once average people could afford it. (**1960**: One million commercial flights in the US. **2005**: Twenty million!) Since then, airlines – and airliner manufacturers – have aimed to minimize fuel burn, as a key competitive tactic.

727-200	**30** MPG per seat
707-320B	**34** MPG per seat
737-600	**52** MPG per seat
767-200ER	**73** MPG per seat
777-200ER	**81** MPG per seat
787-8	**88** MPG per seat
787-9	**102** MPG per seat

Sources:
planes.axlegeeks.com
wikipedia.org/wiki/Fuel_economy_in_aircraft

Piston Engines: the Four-Stroke Cycle

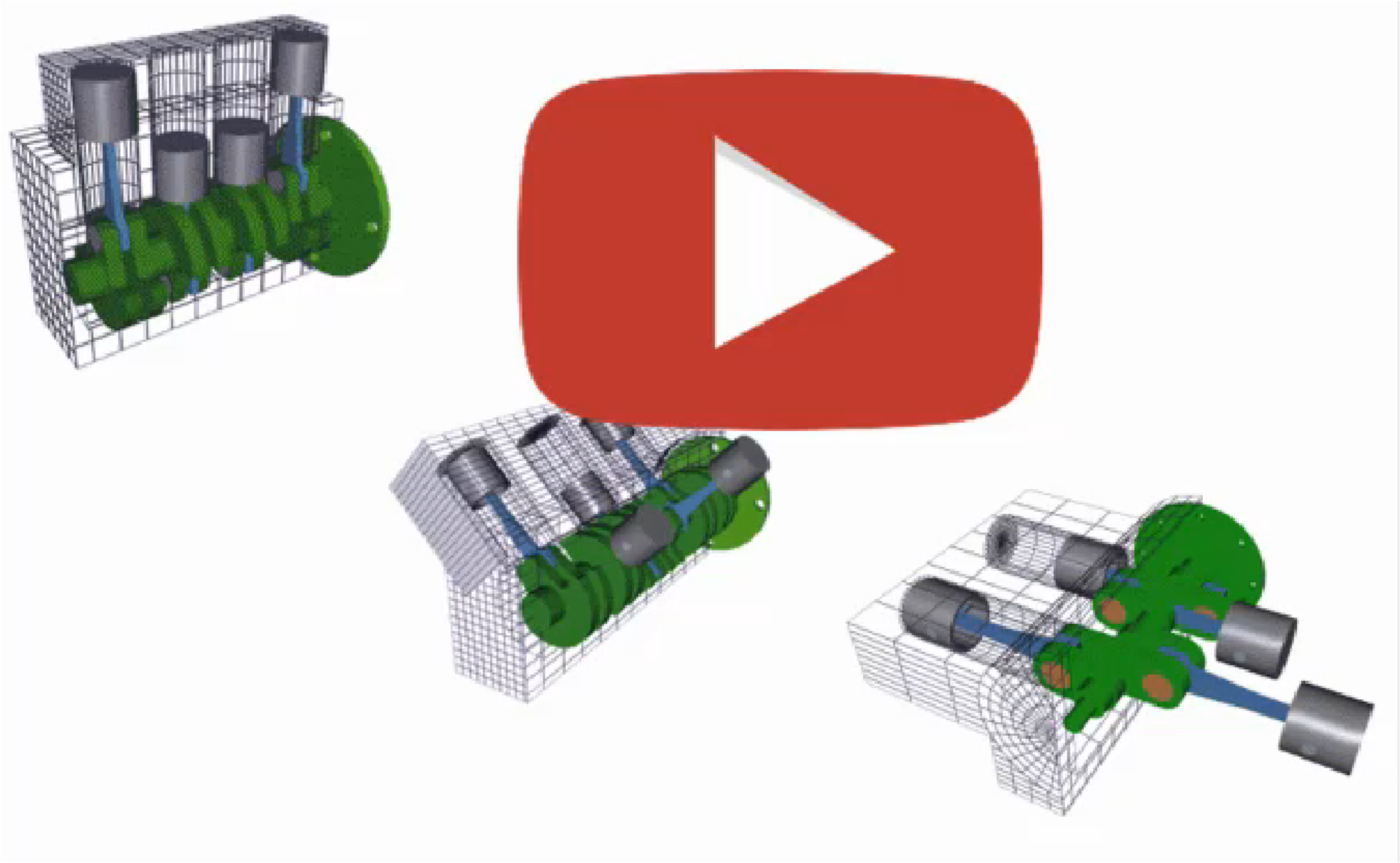




Piston Engines: the Four-Stroke Cycle

- Each piston engine is made of one or more (typically four) cylindrical chambers ("cylinders") each of which has one movable wall ("piston") attached to a rotating axle ("crankshaft"). The wall opposite to the movable wall (the "head") usually has ignition sources ("spark plugs") as well as openings for air, fuel, and exhaust to go in and out (opened and closed by "valves"). Most piston engines use the Otto Cycle a.k.a. the four-stroke cycle:
  - (1) **Intake** stroke: Exhaust valve closes, intake valve opens. Piston moves down, sucking in a mixture of air and fuel from the intake manifold (where fuel was sprayed into the air).
  - (2) **Compression** stroke: Intake valve closes. Piston moves upwards, compressing and heating the air and fuel.
  - (3) **Power** Stroke a.k.a. **Combustion**: Valves are still closed. Spark plugs fire. Air and fuel combust, generating heat and pressure, pushing the piston back down.
  - (4) **Exhaust** stroke: Exhaust valve opens. Piston moves back up, pushing out the exhaust.
- In short, the four strokes are: "**suck, squeeze, burn, blow**".
- Four is a good number of cylinders: At any given time, each cylinder is on one stroke. This means one cylinder is in the power stroke at any given time, supplying power for moving the other three pistons (and the propeller).
- (Some engines use a two-stroke cycle, but those are mostly in motorcycles, scooters, lawn mowers, chain saws, model airplanes… Some ultralights and a handful of small homebuilt airplanes do use them, though, mostly tiny one-seaters. Two-stroke engines generate more power for their weight, but are far less fuel-efficient).

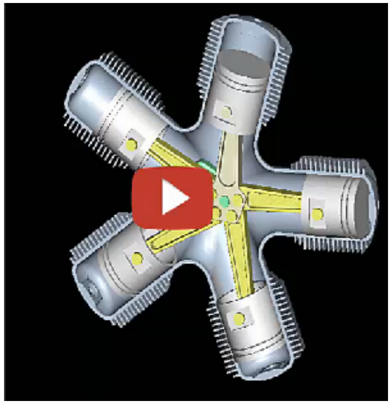
In-Line, V, and Boxer



In-Line, V, and Boxer

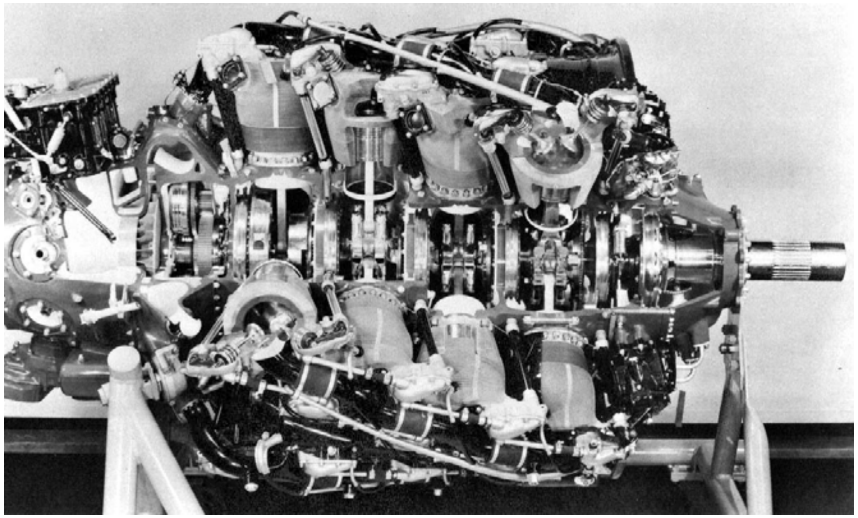
- Early engines arranged all cylinders in a row, i.e. ***in-line***, e.g. the Wright Flyer. Many cars still do this (e.g. Civic, Accord, Camry…).
- Tilting every other cylinder to a different side means the "line" takes up less space, i.e. two staggered lines with half the depth in total. This is a "***V***" engine. (E.g.: One diagonal line of three cylinders, next to a diagonal line of three other cylinders tilted the other way, makes a "V-6" engine, as shown in the previous slide).
- Most modern airplane piston engines have 4 cylinders, and a "V" with an angle of 180°, i.e. ***horizontally opposed*** (similar to BMW motorcycles, Subarus, and some Porsches: CG is nice and low). This is a ***boxer engine***: Pistons move in and out as mirror images, like a boxer punching his gloves together.
- Historical note: In the 1950s, new large and fast airplanes transitioned from having radial engines (and the occasional V-12) to having jet engines (and the occasional turboprop). New small and slow airplanes transitioned to having boxer 4-cylinder (and occasionally 6-cylinder) engines, which were originally used in some 1930s designs like the Piper Cub.

Radial Engines



P&W WASP

P&W WASP MAJOR
("quadruple Wasp" stack)



ROBIN C-1

B-17

F2G SUPER CORSAIR

Radial Engines

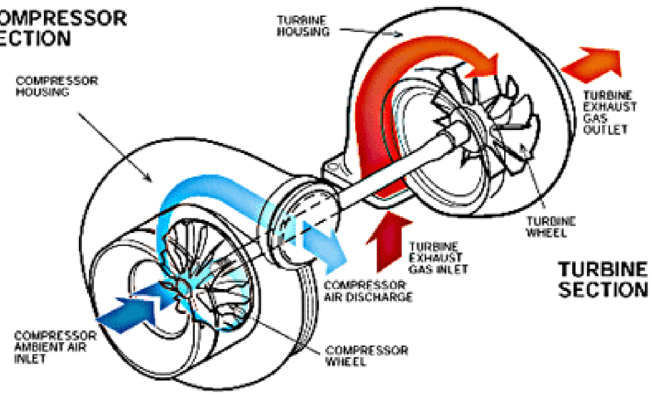
- Most airplane piston engines are air-cooled (unlike car engines that are cooled by oil and radiators): Cylinder heads covered in cooling fins, air blows over them and picks up heat (like motorcycle engines).
- Cylinders towards the back of the "V" are not cooled as well, can't burn fuel as fast ☹
- One solution: Put all cylinders in the "front row", arrange them radially around the crankshaft like the petals of a flower. ***Radial engine***! Can burn more fuel, faster, without overheating! No need for cooling system/radiator.
- Need 2x the horsepower? Stack a radial engine in front of another! They're flat (only one cylinder "deep") so it's relatively easy to do. Some airplanes even had *four* rows of radial cylinders… but then the aft ones get hard to cool, defeating the point of the radial engine. Lots of "long noses" by the end of WW2.

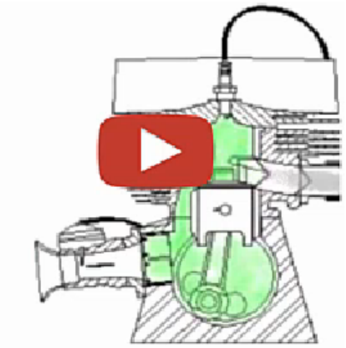
CORSAIR

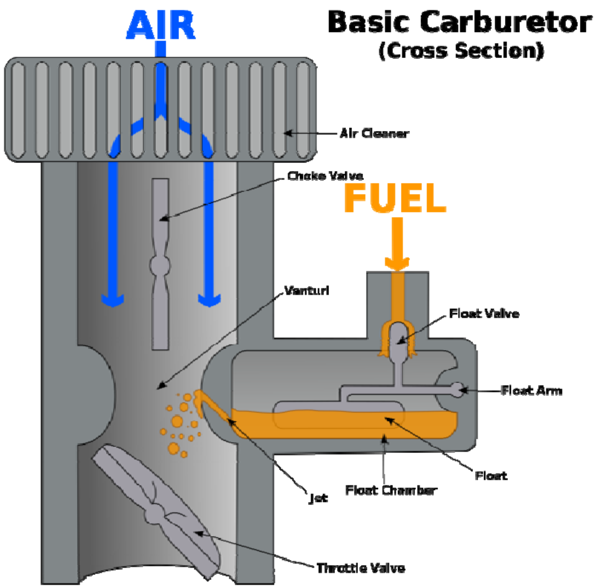
- (Most piston-powered airplanes used radial engines from World War 1 until the 1950s. Exceptions include many fighters and some bombers in the European WW2 theater that used oil-cooled V-12 engines, and some trainers and recreational airplanes that started using boxer engines in the 1930s. By the 1950s, nearly all small airplanes used boxer engines, and nearly all large airplanes used jet engines or turboprops).

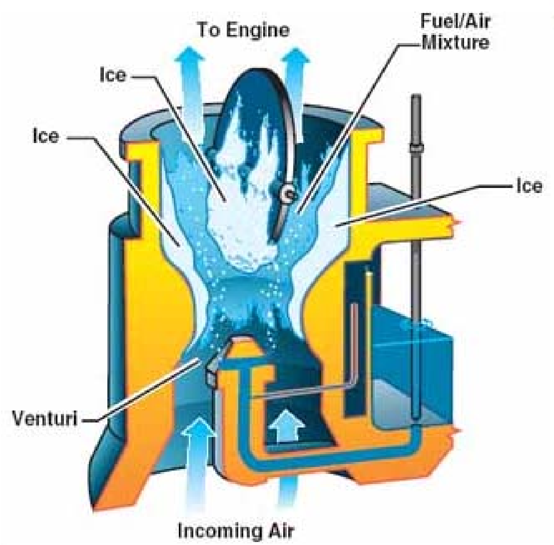
Piston Engines: Miscellaneous

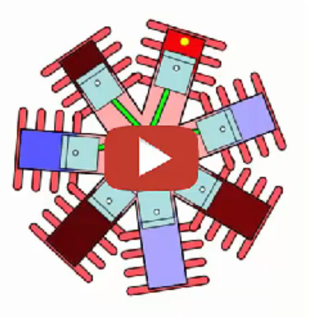

B-17







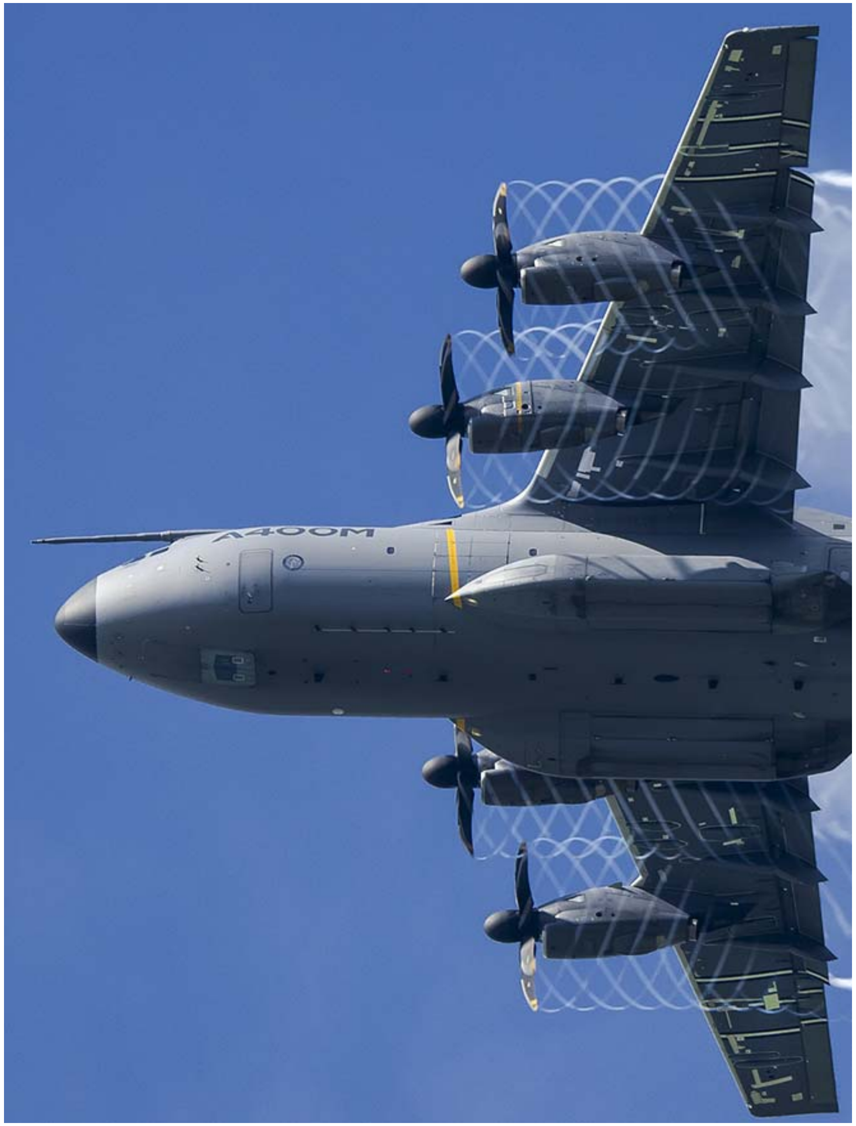


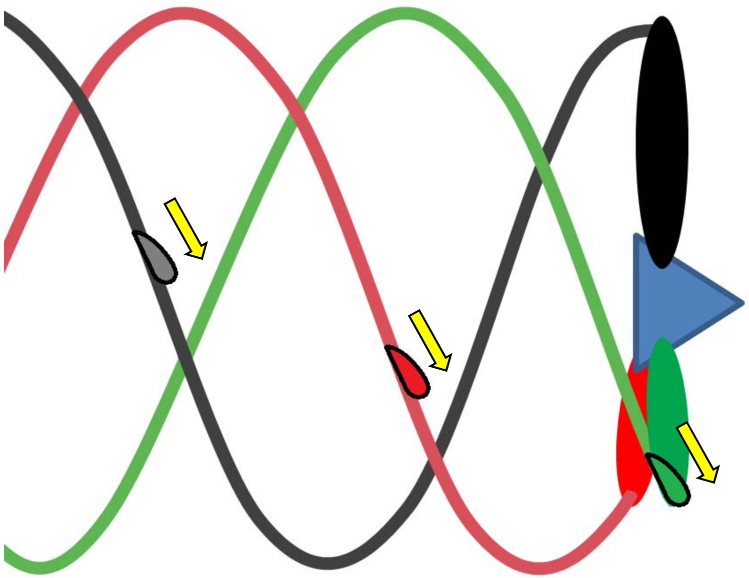


[Personal note: I majored in mechanical engineering. I took lots of classes about engines, and was surrounded for years by people who loved tinkering with cars and engines. I could spend many hours talking about all the clever little features and interesting rare variants of piston engines, but this would probably not add a whole lot of value to this course. However, here is a brief sample].

- ***Balance***: You don't want all the cylinders to go "bang" at once and then not generate any power for a while. It's better to spread out the power strokes over time as evenly as possible, for less vibration/noise. This is why 4-cylinder boxer engines are popular, and why radial engines have an odd number of cylinders.
- You need compression in order to burn fuel. How is an engine started? Either by an electric ***starter motor***, or by hand.
- One way to cool radial engines even more is to bolt the crankshaft to the airplane and the engine to the prop, rather than the other way around. This way, the engine spins with the prop! This is called a ***rotary engine*** (not to be confused with Wankel engines, which are also called "rotary"). This causes huge gyroscopic forces and it's mechanically complex… but it can generate lots of horsepower for its size. Gnome and Rhone rotaries powered many airplanes during WW1. They are "throttled" by turning off one, two three, or more sparkplugs!
- Fuel is sprayed into the air before the air enters the cylinder. This is done by a ***carburetor*** (fuel is sucked by low-pressure air in a venturi) or by a fuel injection system (powered by a pump). How much fuel should be sprayed into the air? ***Stoichiometry*** (i.e. the chemistry of matching up fuel molecules with oxygen molecules) says you get peak power if you spray in just enough fuel to use up all the oxygen. Running ***lean*** (a little less fuel, causing some O2 to be left in the air) is more fuel-efficient but causes higher engine temperatures (i.e. shorter engine life) and emits oxides of nitrogen. Running ***rich*** (a little too much fuel, all the O2 is used up but some carbon and hydrogen from the fuel are left over) is less hot and allows for more power and longevity but is less fuel-efficient and emits (and gets the engine "sooty" with) smog-generating hydrocarbon emissions, and carbon monoxide. Most piston-powered airplanes have a red "***fuel mixture***" knob so the pilot can decide whether to run rich, lean, or "at peak". "Peak" is typically determined by looking at the exhaust gas temperature, which hits its max at peak (best) mixture.
- Carburetor ***venturis*** locally drop not only the air pressure but also the air temperature. If air is humid, water might condense. If air is also cold, condensed water might freeze! This might plug up the venturi, causing a loss in power. Pilots are taught to be on the look-out for ***carburetor ice*** and to turn on "carburetor heat" (re-routing some hot engine exhaust back through the carburetor) if they lose some power. However, carb ice still causes around twenty light-airplane accidents in the US a year, including one or two fatalities. Fuel injection is slowly replacing carburetors, but it's more expensive, and the vast majority of single-engine airplanes are old and will not have their engines replaced or upgraded this way.
- ***Turbochargers and Superchargers*** are pumps that compress air before it goes into the cylinders. Denser air has more oxygen and can burn more fuel, generating more horsepower without the engine needing to be any bigger or heavier. (Well, it needs to be a little heavier in order to safely take the higher pressures). Superchargers are powered by the engine, while turbochargers are powered by a turbine in the exhaust. These are essential for high-altitude flight in piston-powered airplanes, above 25,000 feet or so. Not in widespread use today (since very few recreational or training flights ever go so high), but very important in 1920s-40s and in air-racing.
- The **compression ratio** is the volume inside the cylinder when the piston is down, divided by the (smaller, "squeezed") volume when the piston is up. The higher the compression, the higher the efficiency, the more power… but also, the hotter it gets. Each kind of fuel auto-ignites at some temperature, so **engines with very high compression can only use fuel that auto-ignites at extra-high temperatures. This is what the "Octane" rating refers to**: High-compression engines must use high-octane fuel, otherwise the fuel auto-ignites during the compression stroke, before being set off by the spark plug. Technically: Pure n-heptane auto-ignites at 433°F (octane rating 0%) while pure octane auto-ignites at 745°F (octane rating 100%). A compression ratio of 7 to 1 causes the air in the cylinder to be heated to just over 700°F, requiring fuel with at least 87-octane, typical for cars. Most airplanes require 100-octane fuel (compression ratio 10 to 1, temperature just over 740°F) and some exotic racing engines and fuels can have octane ratings as high as 115 to 130. Their expense, and the emissions from the chemical additives that make this possible, cause such fuels to be impractical for everyday use.
- Some engines use the ***two-stroke cycle***. They are not very fuel-efficient and generate tons of emissions (especially because most of them mix oil in with the fuel for lubrication) but are very weight-efficient: Every stroke is a power stroke, so fuel is burned twice as fast. These used to be exclusive to ultralight airplanes (and chain saws, lawn mowers, scooters, etc.), but have more recently been used on some homebuilts like the Pulsar. Single-seater homebuilts like the Quickie and the AR-5 have actually broken speed and range records for light airplanes (~200mph and ~700 miles!) using two-stroke engines.
- One way to get more horsepower from a smaller engine is to run it at higher RPM. However, the prop should not spin too fast because you don't want the tips "going supersonic". One solution is to have a ***reduction gear***. Some energy is lost in the gear (becomes heat and noise), and it's one more mechanism that adds weight and maintenance actions… but for most modern LSAs (two seats, ~100hp, ~1320 lbs MTOW), it's worth it. They're almost all powered by geared-down Rotax engines. Many airplanes in WW2 had reduction gears, so their engines could be run at higher RPMs without the tips of those huge prop blades going supersonic (or, more precisely, "exceeding their MCRIT and starting to make shockwaves").

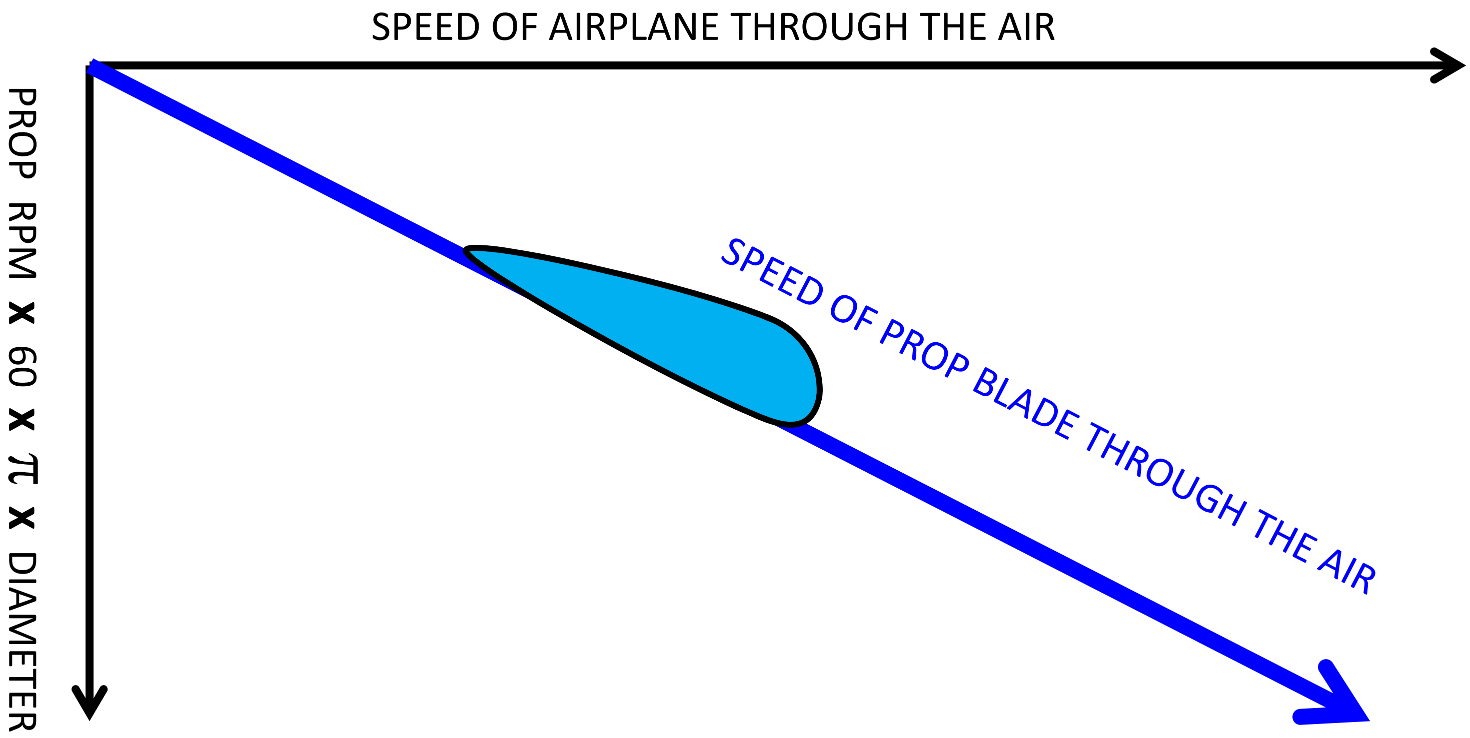
The path of a propeller blade through the air





- Why do most large airplanes use jet engines nowadays, not props?
  To understand the answer, first we must understand the path of a propeller blade through the air.
- Each propeller blade goes around and around, and it also goes forwards.
- This means the tip of each propeller blade traces a helix
  (i.e. a spring or corkscrew) through the air.
- From the side (projection), this looks like a sine wave for each prop tip.
- If each prop tip drew a line through the air… As the propeller in the diagram moves right, you would see the black blade coming down… then as the black blade hits the bottom and starts going up the back, the red blade comes down the near side (the "out of the page" side)… then the red blade hits the bottom and starts going up the back, and then the green blade comes down. The cycle repeats as the black blade hits the top around the back and starts coming down the near side again.
- Each propeller blade works just like a wing. It is an airfoil moving through the air at some angle of attack, and making "lift" in the perpendicular direction. So as each blade moves down (and somewhat forwards diagonally), it makes lift forwards (and somewhat upwards), pulling the propeller forwards (and somewhat resisting its motion through the air, i.e. drag).

Why can't prop planes go fast?



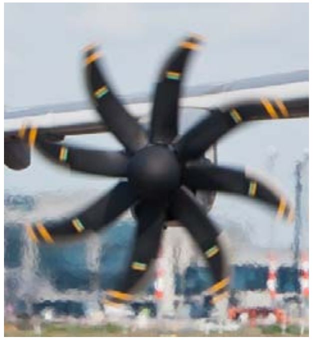
Why can't prop planes go fast?

- The drag of propeller blades (like anything else) rises dramatically as they approach the speed of sound [~1100 ft/sec]. This limits prop RPM to
  *(60 seconds / minute) *1100 feet / (π x prop diameter)*
- As an airplane goes faster, this gets even lower. By the pythagorean theorem,
  *(speed of prop through air)² = (RPM*60*π*diameter)² + (airplane speed)²*
- If there were a strict requirement to keep prop blades subsonic:
  Once the prop plane is at Mach 1, you couldn't spin the props around at all!

- In practice, it's not so bad: Propellers can be shaped for supersonic flow (e.g. swept tips with thinner and/or supercritical airfoils) and their drag can be overcome by brute horsepower.
- In fact, at max power (i.e. during takeoff), prop blade tips do go fast enough to make shockwaves. More than half the noise of a propeller airplane taking off are the little sonic booms from the blade tips, not the sound of the engine itself.

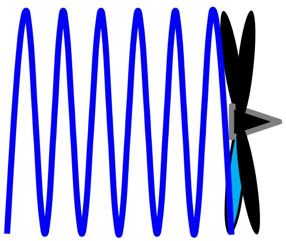
A400M SWEPT PROPS

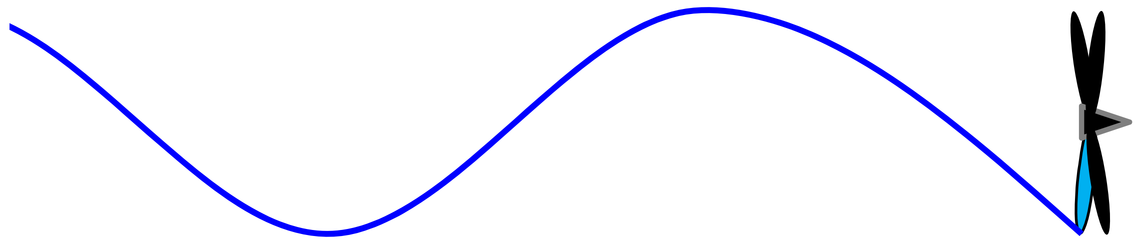
Why can't prop planes go fast?

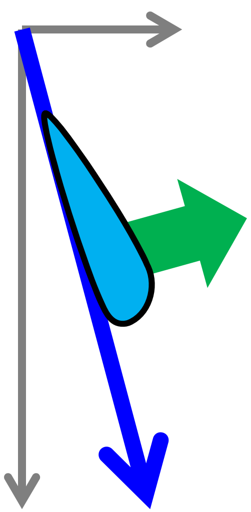


AIRPLANE FLYING SLOWLY

AIRPLANE FLYING AT HIGH SPEED



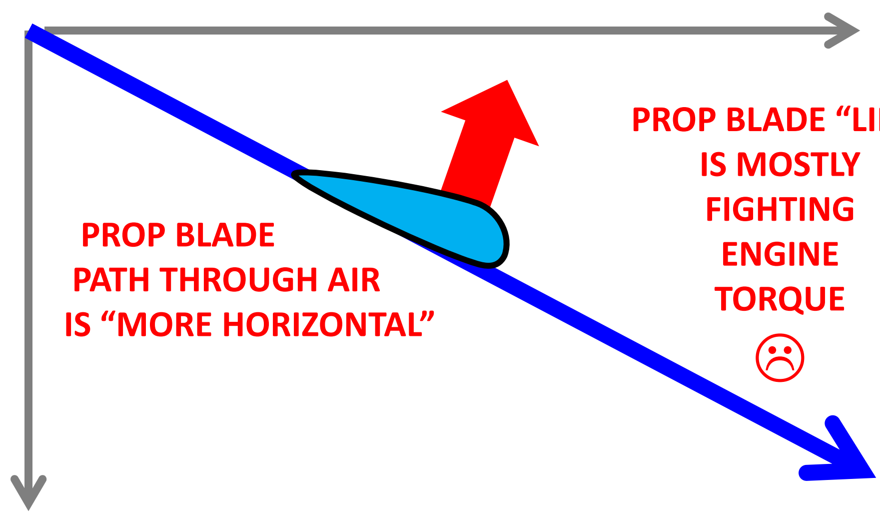




PROP BLADE PATH THROUGH AIR IS "MORE VERTICAL"

PROP BLADE "LIFT" IS MOSTLY FORWARDS THRUST

☺



PROP BLADE PATH THROUGH AIR IS "MORE HORIZONTAL"

PROP BLADE "LIFT" IS MOSTLY FIGHTING ENGINE TORQUE

☹

Why can't prop planes go fast?

- The main problem with props at high speed, even worse than Mach effects, is related to the angle of the blades slicing through the air in a corkscrew. The angle is diagonal, but… is it closer to vertical, or closer to horizontal?
- When the airplane is stationary or very slow, the prop slices the air vertically, and all prop blade lift (i.e. thrust) is straight forwards.
- **As the airplane goes faster, the angle of the prop blade path becomes closer to horizontal, so more of the prop blade lift is in the vertical direction the prop blade came from, i.e. fighting the engine torque, and less of the prop blade lift is pulling the airplane forwards as thrust.**
- The only way to steepen the corkscrew angle again is to increase engine RPM, but that causes the shockwave issues discussed earlier.
- So **the faster a propeller airplane goes**, either the engine must push harder in order to fight the increasingly adverse lift from the prop blades, or the engine must push harder in order to achieve higher RPMs which involves pushing a larger fraction of the prop blades supersonic. In any case, **efficiency decreases**.
- It's theoretically possible to design a supersonic prop plane, but it would require impractical amount of engine power. The airplane would be a "flying engine" with very limited range and little endurance. Even the XF-84H could not break the sound barrier.

Props VS Jets

Props VS Jets

- Small airplanes use props, large airplanes use jets. Why?
- **Jets get more efficient the faster an airplane flies**, due to "free" compression at the inlet.
- **Props get less efficient the faster an airplane flies**, due to lower RPM (if tips are to remain subsonic) and to less prop-blade lift in the forwards direction.
- So for missions that require **high speed** (e.g. fighters), jets are the clear winner.
- For missions that require **endurance** but not speed (e.g. surveillance and most flight-training and recreational flying), props are the clear winner.
- For airplanes where slow-speed characteristics (e.g. being easy to land, and not too expensive to fly per hour) are more important than high speed, and that are almost only ever flown in short trips (so fast speed would not save much time), props are often the winner.
- What about for "in-between" missions... e.g. airliners? Why are large airliners jets while small ones are turboprops?

Props VS Jets

B-36 (1946)
Max weight: 410,000 lbs
Empty weight: 166,000 lbs
Range: 10,000 miles
Cruise speed: 230 mph
(Endurance >40 hours!!!)

B-52 (1952)
Max weight: 488,000 lbs
Empty weight: 185,000 lbs
Range: 10,145 miles
Cruise speed: 525 mph

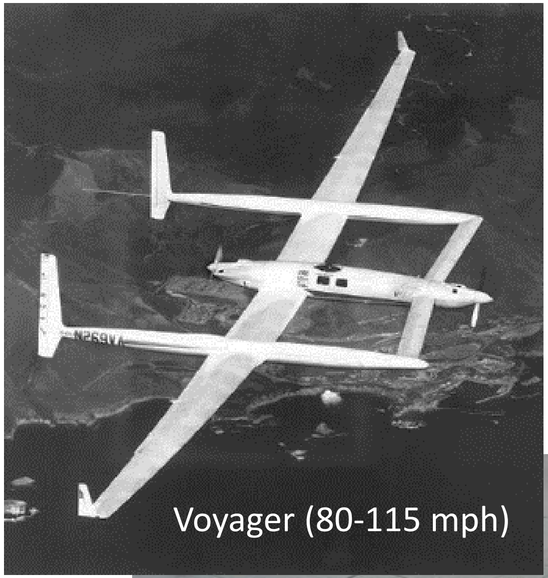
Props VS Jets

- Which airliners use props and which use jets? It depends on how much people value their time.
  - Take a 7500 mile flight. It can be flown in a propeller airplane in 30 hours… or in a jet plane in 14 hours, for maybe 30% higher cost. Which would you rather pay: ~$1000 for a 30-hour flight, or ~$1300 for a 14-hour flight? You'd probably choose the shorter flight. You'll want those hours of your time. (And so would most people who can afford such a long flight to begin with).
  - Take a 300 mile flight. It can be flown in a propeller airplane in an hour, or in a jet plane in half an hour, for maybe 50% higher cost. (With a shorter flight, more of the flight takes place at low altitudes and slow speeds, where props have especially high efficiency and jets have especially low efficiency). Which would you prefer? ~$100 for a one-hour flight or ~$150 for a half-hour flight? Probably the cheaper one. Who cares about half an hour? Save some bucks. (Especially given that the half-hour difference in flight time is not such a huge difference in door-to-door time. Between packing, driving to the airport, parking, checking in, going through security, waiting to board, taxiing, flying, taxiing back, getting your bags, getting your car, and driving to your destination… a reduction in flight time of only *half an hour* is nothing. It's lost in the noise).
- In short: **The longer the flight, the more time is saved by a jet plane rather than a prop plane, and the more people will be willing to pay a little extra for this.**
- However, other factors come into play:
  - The military may prefer large propeller airplanes because they are less prone to damage from dust and small rocks while operating from unimproved airfields.
  - The airlines may prefer jets (even small, short-range ones) over turboprops because jets are more reliable, cheaper to maintain, and can keep flying in worse weather.
  - The airlines may prefer faster airplanes because they can do more flights per day (less time per flight) for each airplane and crew, i.e. the airline can replace their turboprops by half as many jets (and half as many pilots) and still do all their flights every day. (Well, maybe not *half,* but fewer).

Should we slow back down?

Easiest way to increase fuel efficiency and reduce per-mile costs
without having to develop new technologies:

NASA/Boeing SUGAR



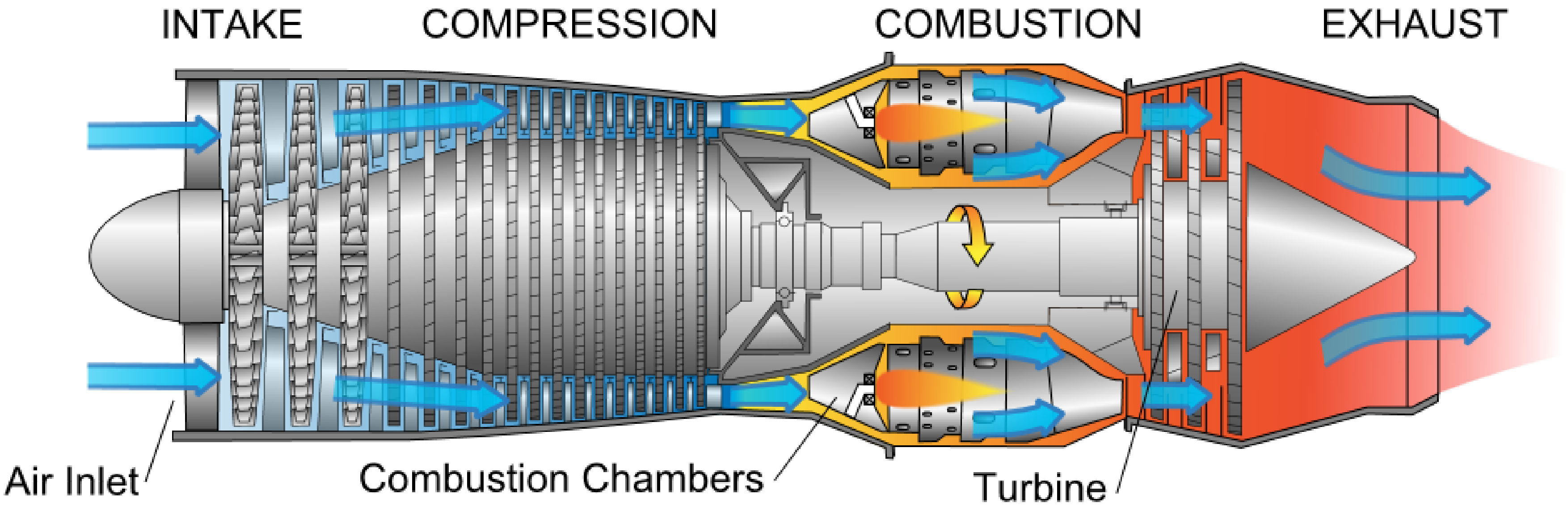
Voyager (80-115 mph)

Optimized for range
(i.e. fuel efficiency)
above all else:

Global Flyer (~350 mph)

- There are a lot of new technologies that, the more they are developed, the more fuel-efficient airliners become. Wider and geared turbofans [slides 274-277], and hotter engines with more compression [slide 273], make thrust with less fuel. Lighter materials [slide 155] and stronger structural configurations [slides 158-185] allow for less weight (i.e. less induced drag), for higher-aspect-ratio wings (even less induced drag [slide 117]), and more payload (i.e. more passengers to split the fuel bill). Systems are becoming more energy-efficient. Various features are tweaked to reduce drag [slides 94-99,102-105,124-127,134-141]. Airports are studying steeper, low-power "gliding" approaches to land [see "Tailored Arrivals" in the "Latest Developments" slides under "Special Topics" at UnderstandingAirplanes.com].
- But all these things have to be invented, then optimized, then made safe and reliable. This takes time, costs millions of dollars, and may or may not pay off.
- **One way to drastically reduce fuel burn right now, with zero R&D costs, would be to slow down.**
- Look at record-breaking airplanes that were uncompromisingly designed for range (i.e. fuel efficiency) above all else. They cruised at 80 to 360 mph, not at jetliner speeds (~560mph).
- Propellers are VERY fuel-efficient at up to 200mph. Small jets do great around 300mph.
- But would people be willing to take a 10 or 15-hour flight across the US?
- Most people soon may not have a choice. Look at how the income and wealth distributions in the US have been changing: The middle class is sinking. Most people have less and less disposable income for things like travel. Many experts say that, in 10-20 years, the only way that a big chunk of the population could afford long-distance flights is in super-efficient slow turboprops.
- Boeing has been studying this concept ("SUGAR Volt"). When the market demands a slower airplane (i.e. cheaper tickets at any "cost"), airplane manufacturers want to be ready to deliver such a plane.
- (At those speeds, induced drag is a bigger problem than viscous drag. Hence the wing struts / braces: As Cessna can tell you, a little extra surface area for that strut is worth it at slow speeds because it allows for high aspect ratio wings, lighter structural weight, thinner wings, or some combination thereof).
- Ok, enough about "jets versus props". Now… How exactly does a jet engine work?

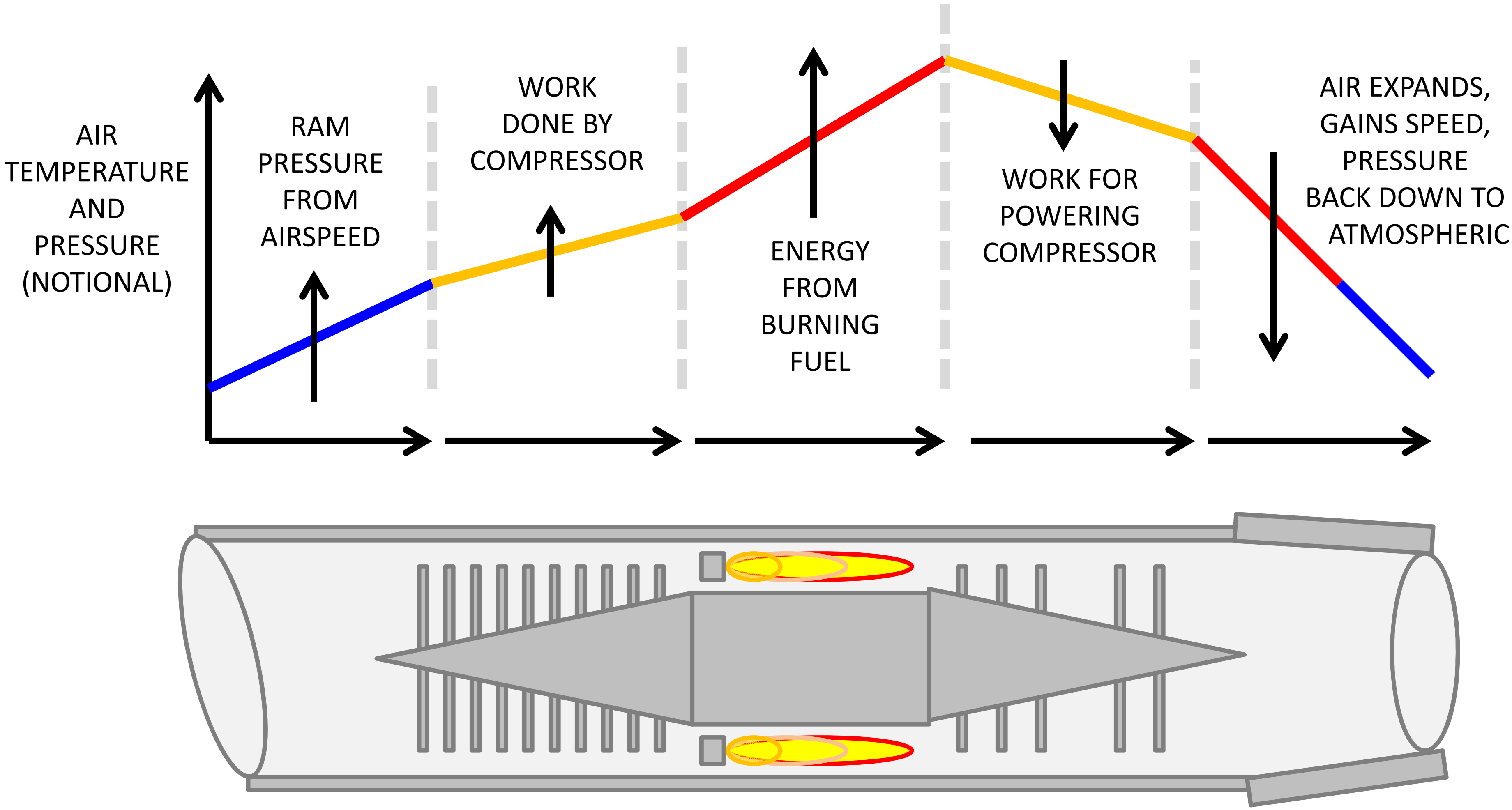
Jet Engine


INTAKE
COMPRESSION
COMBUSTION
EXHAUST
Air Inlet
Combustion Chambers
Turbine

Jet Engine

- Actually has the same "steps" as the piston engine, except all processes happen at once rather than one at a time.
- Inlet, compressor, combustor, turbine, nozzle.
- The ***inlet*** slows down the air, which raises its pressure and temperature a little (or "a lot" if the airplane is supersonic). The compressor and combustor work more efficiently if the air is slower.
- The ***compressor*** compresses the air using a series of fan blades, significantly increasing its pressure and temperature.
- The ***combustor*** sprays some fuel into the air and burns it, increasing the pressure and temperature as much as the engine's materials can stand. The air now really wants to expand.
- The ***turbine*** (basically another word for "windmill") is blown by this hot expanding air, taking just enough energy to spin the compressor.
- The air expands out the ***nozzle***. The cross-sectional area is carefully chosen so that, by the time the air exits the back, it has been sped up by the right amount so that its pressure is down to one atmosphere. (Any higher pressure and the air has "extra pressure" that could have been turned into speed and thrust, but instead will just make a plume. If the pressure is lower than one atmosphere, then the air was over-accelerated, the edges of nozzle will "stall", and air will try to come in the back).

Compressors and Efficiency

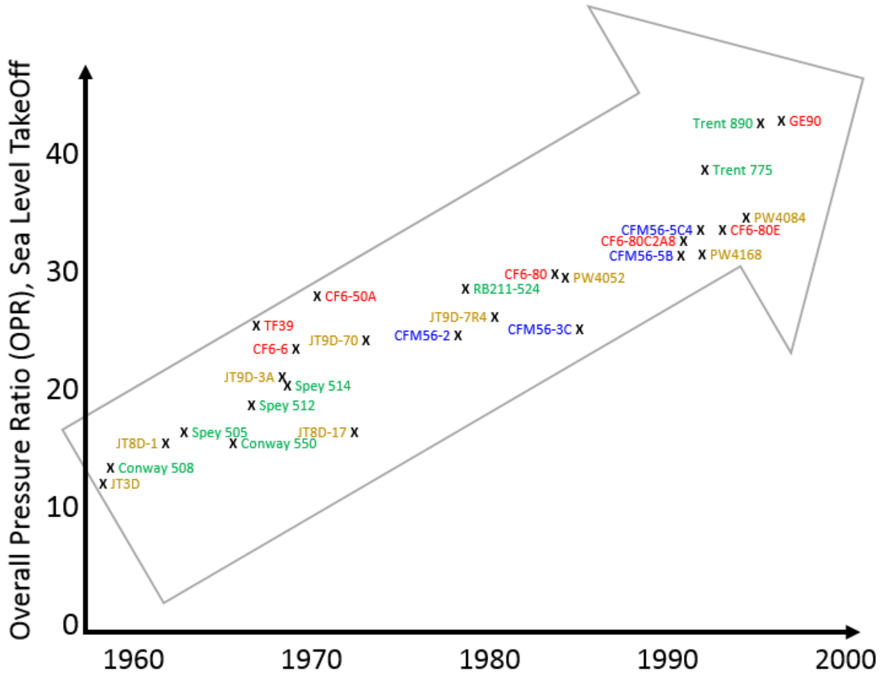


The more work is done by the compressor, the higher the efficiency.
But the faster you go, the more ram pressure energy you get from the airspeed, and the less work the compressor can do before overheating.

Compressors and Efficiency

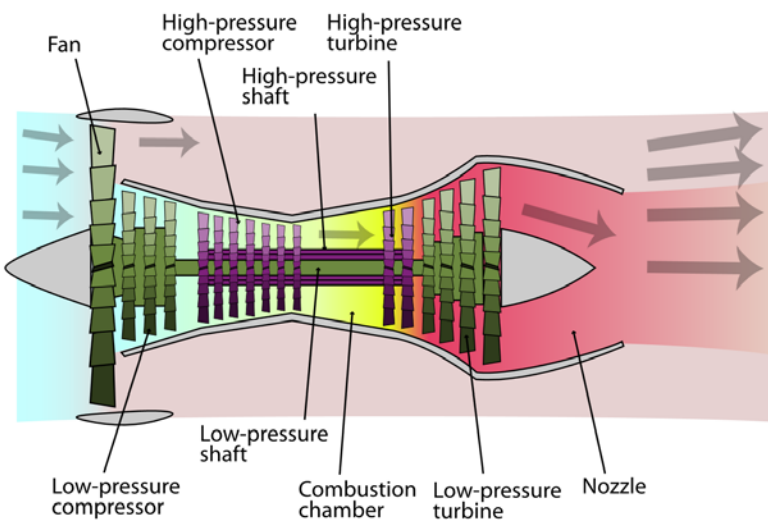
- The higher the overall ***compression ratio*** (ratio between pressure during combustion, and pressure out in the atmosphere), the higher the thermodynamic efficiency of the jet engine. (Piston engines, too).
- Subsonic airplanes have powerful compressors: about 40x compression:
- A more powerful compressor would be more efficient… but it would cause higher temperatures, meaning that less fuel could be burned [per cubic foot of air] without the engine overheating. This would require the engine to be bigger overall (so that enough fuel could be burned in total) and thus heavier. As materials become more lightweight and more temperature-resistant, it becomes worthwhile to equip airliners with more powerful compressors for higher fuel efficiency:

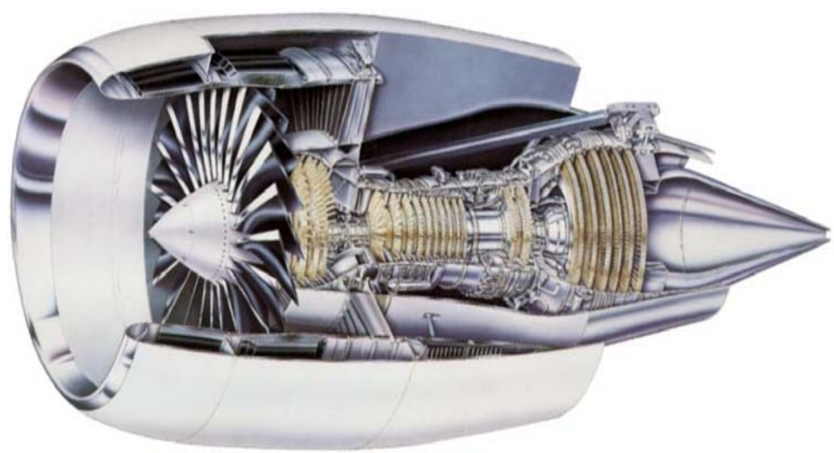
- Some compression happens in the compressor, but some compression happens in the inlet too. ***The faster the airplane goes, the more compression happens at the inlet, and the less compression can happen at the combustor before the turbine overheats***.
- Fighter compressors only compress the air about 20-25x. This makes them less fuel-efficient during subsonic flight, due to low compression. They are also less fuel-efficient during supersonic flight due to high drag… but at least they can get there without overheating the turbine!
- Ramjet engines and old fighter jets' afterburners run on inlet compression alone. (New fighters have small turbofans, which contribute a little compression, but not much). So they are less fuel-efficient (due to the low pressure ratio) but can burn a ton of fuel and reach high speeds without overheating any turbines.



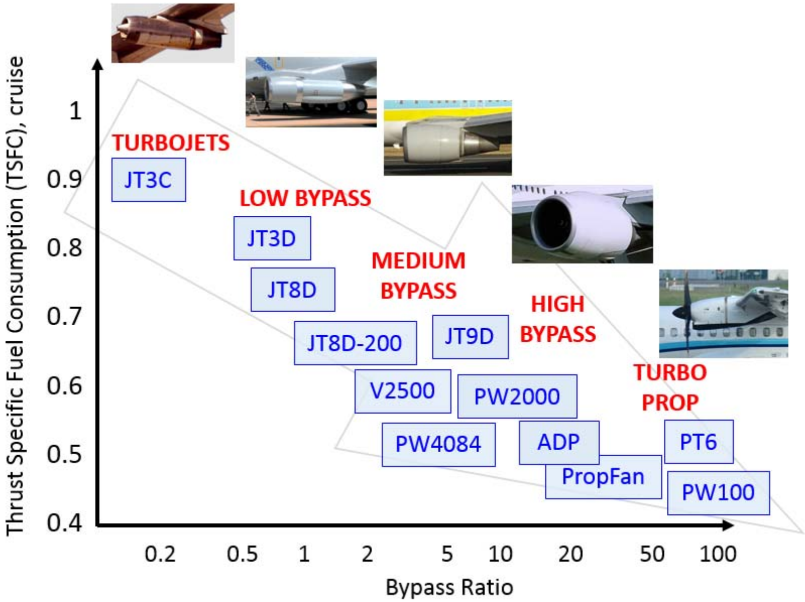
Turbofans

747-8i (GEnX)





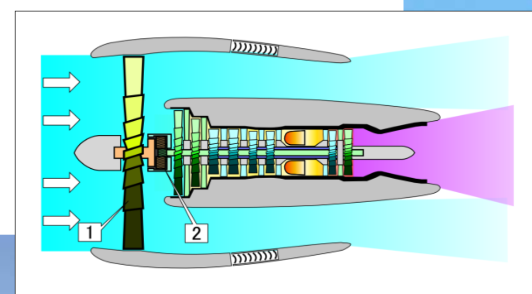
- Transport jets have ***turbofans***. An extra “low-pressure turbine” near the back spins at a low-ish RPM and powers a big fan near the front (as well as maybe some of the compressor). The bypass ratio is between 5:1 and 9:1, i.e. only 10%-20% of the air goes through the compressor, combustor, and turbine. The other 80%-90% just gets blown by the fan, around the “core” of the engine.
- Why are turbofans so fuel-efficient?
  - Thrust force has to do with how much momentum is added to the air. It is the mass of air that goes through the engine each second, times the speed that is added to that air.
  - Power (which comes from fuel burn) has to do with how much kinetic energy is added to the air. It is half the mass of air that goes through the engine each second, times the *square* of the speed that is added to that air.
  - So **if you move more air by less, you get more thrust for less power**!



- Why? For example: Take an old jet engine, and make a new jet engine by increasing its diameter by 1.414, so that you double the inlet area and thus double the mass-per-second of influenced air at cruise speed. Say that the new engine only adds half as much backwards speed to the air as the old engine. Mass per second goes up by 2, speed goes down by 0.5. So thrust is the same (2*0.5), but power is halved (2*0.5*0.5). Or, multiply the old backwards speed of the exhaust air by 0.707. You get 1.414 times the thrust (2*0.707) for the same fuel burn (2*0.707*0.707).

Geared Turbofans, Turboprops, and Un-Ducted Prop-Fans

Geared turbofan. [1]: Fan. [2]: Gearbox.

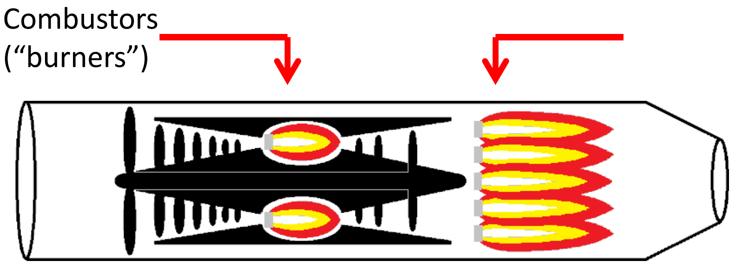


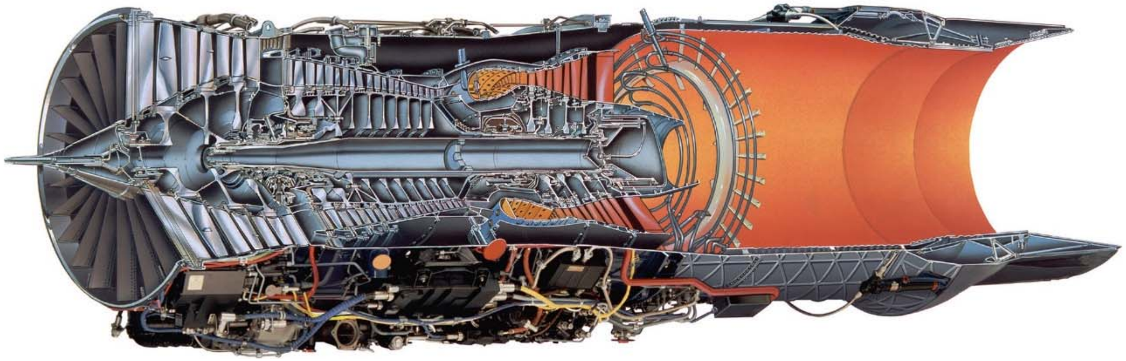
Geared Turbofans, Turboprops, and Un-Ducted Prop-Fans

- You may have noticed that most new narrowbody airliners (CS100, A320NEO, Mitsubishi MRJ, Embraer E190-E2, COMAC C919, Irkut MC-21) use geared turbofan engines.
- You may have heard that around 1980, manufacturers experimented with turbofans without a duct around them. The Antonov 70 acutally uses this kind of engine. (Interesting story! For more info: http://www.airspacemag.com/history-of-flight/the-short-happy-life-of-the-prop-fan-7856180/)
- You may have wondered what the difference is between such engines and the turboprops found in small airliners.
- There are three parameters in question:
  - Is there a duct around the fan?
  - Is the fan geared? (Does it spin more slowly than the turbines that power it?)
  - Does a significant fraction of the thrust (>10%) come from the jet exhaust, or do the turbines absorb all useful energy from the air (bringing it all the way down to atmospheric pressure and a very slow speed) and use all available energy to power the fan?
- If all the thrust is from the fan (i.e. No energy [speed or extra pressure] is left in the exhaust by the time it exits the engine; Some “extra turbines” convert all of the exhaust’s energy into shaft power), then it’s a **turboprop**. These are always geared (but there could be exceptions someday). Modern helicopters use turboshaft engines, which are basically the same thing. They never have a duct around the propeller, except for a couple of VTOL prototypes that did use “ducted fans” (e.g. X-22, VZ-4).
- If there is no duct around the fan, and some thrust comes from the exhaust, then it’s a very rare and exotic **unducted propfan**. (These are sometimes geared, sometimes not).
- If there is a duct around the fan, and some of the thrust comes from the jet exhaust, then it’s a **turbofan**, which in airliners is not geared (except for the BAe146, CS100, Neo, MRJ, etc.)

Why can turbofan airplanes fly faster than propeller airplanes? Because the inlet duct slows the air down. At a given flight speed, an unducted propeller would have to deal with faster-moving air than a ducted fan (e.g. turbofan) would. So the inlet duct alleviates the problems from slides 260-263.

Afterburners



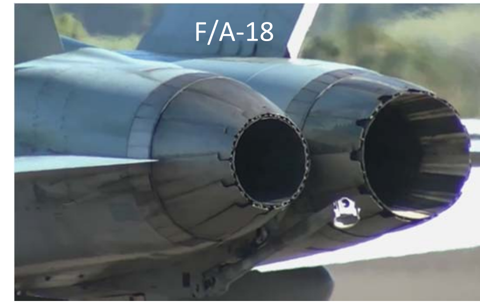


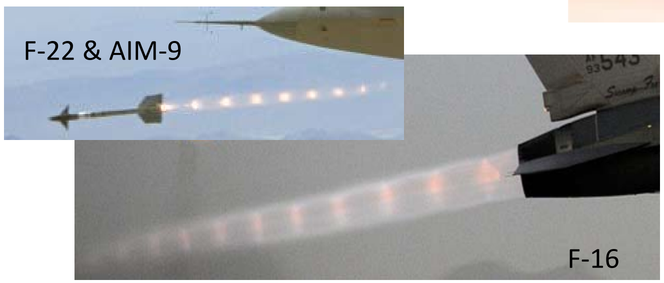
F100-PW-229 ENGINE (F-15E, F-16 post 2009)

Afterburners

- Fighters have afterburners, which basically just **spray more fuel into the tailpipe** and burns it there for extra thrust. This roughly doubles the thrust but dramatically reduces fuel-efficiency: Most fighters could only run the afterburners for 15-20 minutes before the tanks are dry.
- Why are afterburners so inefficient?
  Because the fuel is burned in air that is not at high pressure.

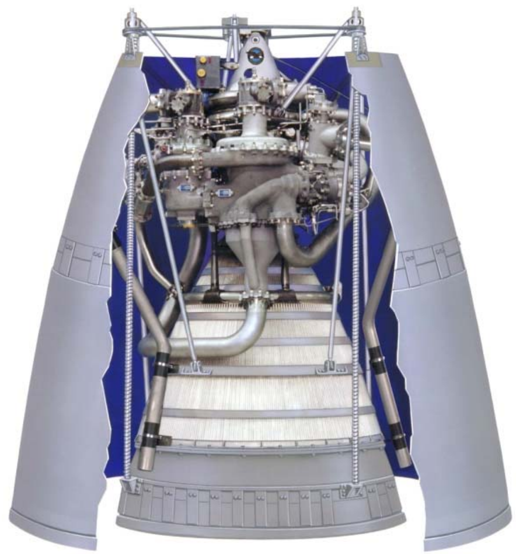
Nozzle Geometry





SHOCK DIAMONDS / MACH RINGS

RL-10 ENGINE
(SATURN I & CENTAUR
UPPER STAGE)
WITH EXPANSION



737 ECODEMONSTRATOR

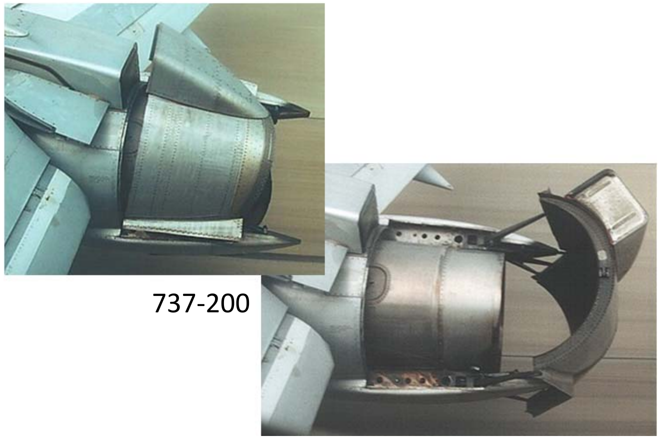
Nozzle Geometry

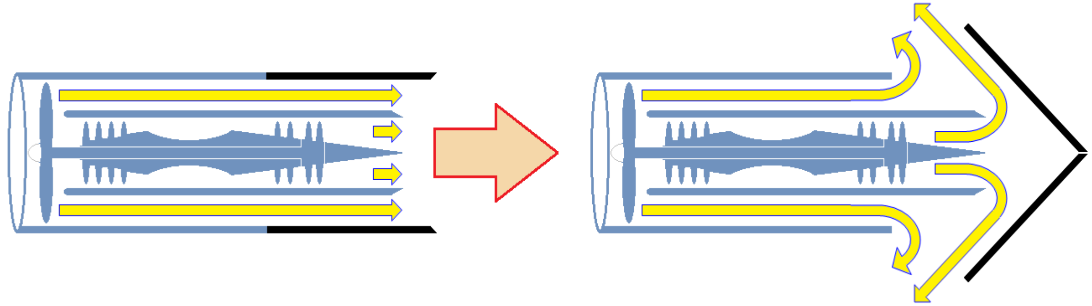
The key function of a nozzle is to convert the exhaust gas pressure into speed

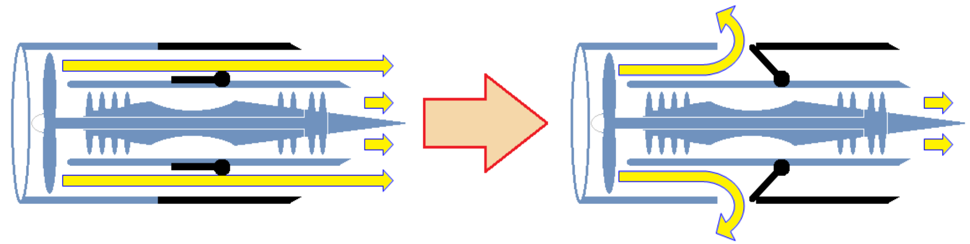
You want the exhaust gases to leave the back of the nozzle at the same pressure as the air outside. Too much pressure, and they'll expand in a plume or in Mach diamonds (and you waste energy). Too little pressure and outside air will try to push its way around the edges of the nozzle (i.e. "stall" it).

- Remember Bernoulli's principle: The narrower the nozzle, the faster the gas goes, and the lower its pressure.
- For compressible (supersonic) flow, the mass balance that underlies the Bernoulli principle breaks down and basically reverses: The wider the nozzle gets, the faster the air goes, and the lower its pressure. So if you have supersonic exhaust, you want a divergent (bell-shaped) nozzle, e.g. on rockets and on afterburning fighters.
- So for supersonic airplanes, **you want a nozzle that can be narrow when the flow is subsonic, and wide when the flow is supersonic**. This is why fighter jets have nozzles made of segments ("turkey feathers") that can make the tube narrower (at slow exhaust speeds) or wider (at high exhaust speeds).
- At higher altitudes, air is at lower pressure. **So you want a nozzle that accelerates the exhaust more (lower pressure) at higher altitudes and less at lower altitudes**. Most rockets and subsonic jets can't do this: Most subsonic jets over-accelerate at low altitudes (part of why airliners are not very efficient at low altitudes) and most rockets under- accelerate at high altitudes. This is why rockets make wide "jellyfish-like" plumes at altitude: Lots of extra pressure. Some rockets have "telescoping" nozzles a.k.a. nozzle expansion: Up near space, additional rings slide onto the end of the nozzle to make it bigger: more expansion, lower pressure. Boeing's 737 EcoDemonstrator studied something similar for airliners.
- If a nozzle dealing with supersonic exhaust does not speed it up enough, or speeds it up too much, you get "overexpansion": The exiting gases will either contract (if too fast, with too low pressure) or expand and then bounce back inwards (if too slow, with too high pressure), they'll get hot and glow, then expand outwards, then over-do it and contract inwards again, get hot and glow, expand again, bounce back in again, get hot and glow again, expand again… this will look like a series of doughnuts or **"shock diamonds" or "Mach rings"**.

Thrust Reversers


737-200





FOKKER 100

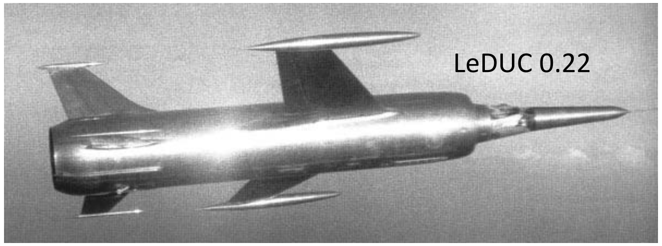

A320


C-17

Thrust Reversers

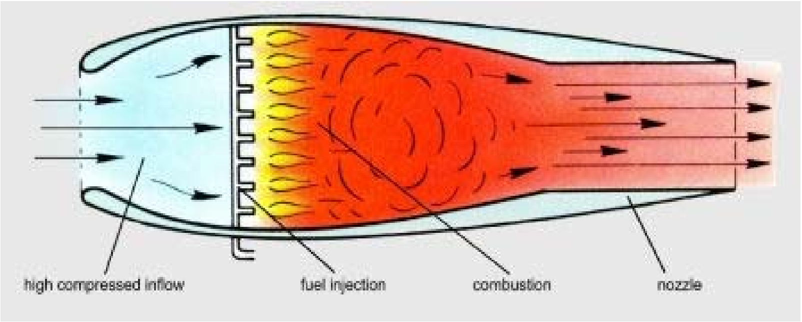
- Most airliners and business jets, and many other airplanes, have thrust reversers: Upon landing, an alternate path (not the nozzle) opens up **for engine exhaust to exit the engine towards the forward direction, to help the airplane slow down after landing.**
- Some airplanes (mostly older jets and business jets) use "clamshell" thrust reversers at the nozzle at the back. Others (mostly newer airliners) use doors along the sides of the nacelles to redirect turbofan flow, often with the aft nacelle sliding backwards to expose the Thrust Reverser channels.
- On dry runways, the wheels provide nearly all the braking force (~90%). However, on wet runways and especially when there is ice, thrust reversers significantly shorten the stopping distance.
- Many airliners and military transports can taxi backwards this way.
- Many turboprops can pitch their blades to a negative angle of incidence to generate negative thrust.

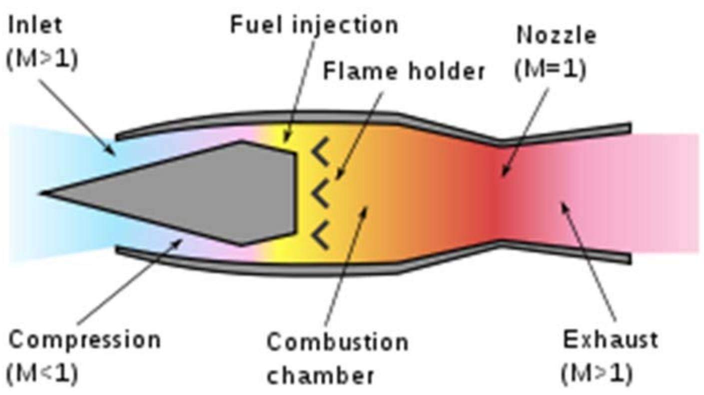
Exotic Engines – Ramjets

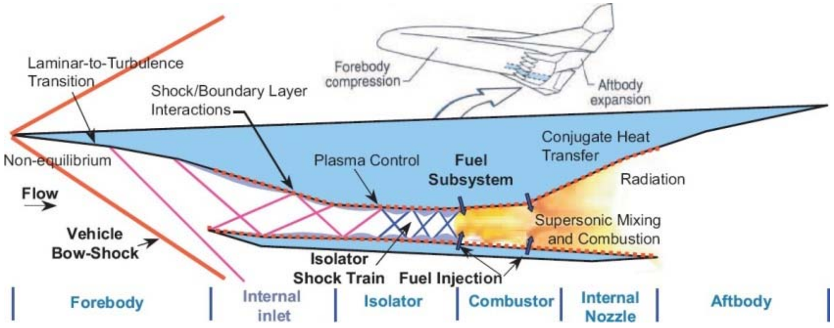


Exotic Engines – Ramjets

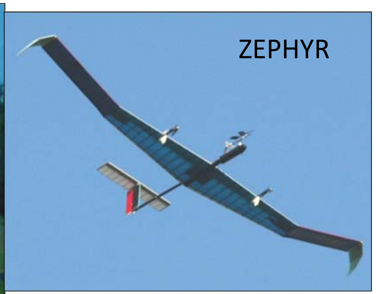
- **Ramjets**: A jet engine with **no moving parts**, only a hollow tube (and often, a spike to help with inlet compression). Only works while going fast enough for inlet compression to get the air hot enough for combustion. **At zero speed, you get zero thrust**. Used on a couple of experimental helicopters (rotors spun up on ground) and drones and missiles (boosted to speed by a rockets or a B-52). A couple of French prototypes had a turbojet for slow speed flight and a ramjet for high speed flight. The Blackbird engine is basically a turbojet sitting inside a ramjet .
- **Scramjets**: It used to be that a jet engine (including ramjets) could only work if the flow inside was subsonic. This only allows speeds up to about Mach 4: Any faster, and slowing the air down to below Mach 1 would heat it too much for any existing materials. So if an engine can **sustain combustion in supersonic air**, that would allow an airplane to go faster without melting the engine. The X-43 reached Mach 10 briefly, and the X-51 could fly for four minutes, which gets you a long ways at a mile per second.







Electric Airplanes & Solar Power

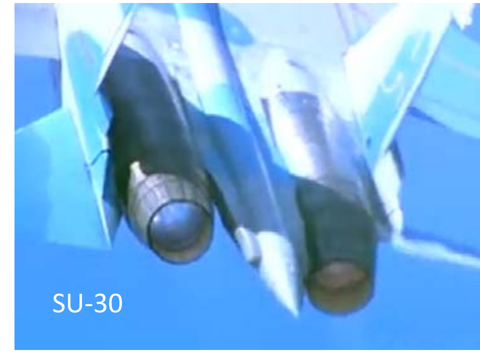


Now for ***really*** exotic engines! Would it make sense to use these in commercial airplanes?

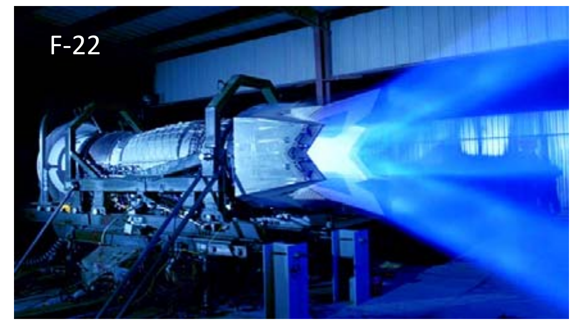
- **Electric**: We have electric cars, why not electric airplanes? Because **batteries' energy density is very low: A given weight of batteries carries 5%-10% of the energy of that same weight in fuel.** (A car's gas tank weighs less than 100 lbs when full: ~15 gal x ~6 lbs per gal. But a Tesla's battery weighs… ~1400 lbs). This means electric airplanes must either (A) have very short endurance, only 5%-10% that of an otherwise identical avgas-powered airplane (e.g. electric EZ, Cri Cri, and SportStar)… or (B) be **designed to fly using extremely little power**, i.e. be extremely lightweight, **slow, and glider-like** (e.g. Electraflyer ULS, eGenius, Taurus) or ultralight-like (e.g. eSpyder, Lazair). The vast majority of electric airplanes are single-seater proof-of-concept airplanes (e.g. PC-Aero, E-Fan). However, over the past few years, a few have flown that could carry two people for about an hour; Enough to be attractive for flight-training: E-Fan, Yuneec, Pipistrel WattsUp, Itaipu Sora-E. We'll see if these go into production. (They're about 15 times as expensive to buy as a used Cessna 152. Buy an old Cessna instead, and you'll save enough money to buy a lifetime of avgas…)

- **Solar**: Solar airplanes have a **strict speed limit**. Each square foot of surface can only generate so much power. But the faster it goes through the air, the more viscous drag pulls on each square foot. At about 60mph, you just can't go any faster: **All the solar power available per square foot would be needed to fight the drag on each square foot of surface**. Given that (A) solar cells are not 100% efficient, (B) the airplane's surfaces cannot all be 100% covered with cells that all see sunlight, and (C) you probably want to store some energy for flying through the night… Practical speeds will be in the **20mph-45mph** range. This is doable, but it's arguably impractical for transportation. However, it's good for **HALE (high altitude long endurance)**: The Qinetiq Zephyr is studying the possibility of a solar-powered military UAV; it has done flights of over 14 days! The NASA Helios has flown higher than any other airplane. And the Solar Impulse is being flown around the world (with stops!).

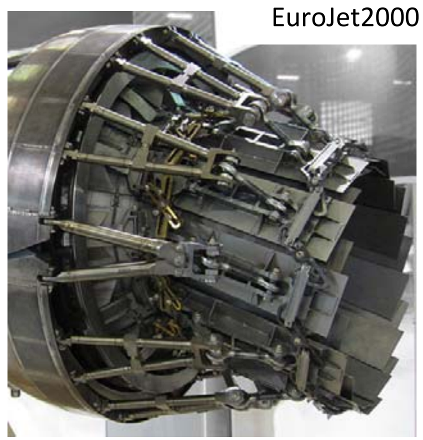
Thrust Vectoring



SU-30



F-22



EuroJet2000

X-31

Su-35

Thrust Vectoring

- Some nozzles – specifically in the, X-31, F-15ACTIVE, F-18HARV, F-22, and some jets in the Su-27 and MiG-29 family – can point the exhaust in directions other than “backwards”.
- This allows these ***nozzles to act as control surfaces*** and to point the jet exactly where the pilot wishes, regardless of the speed or direction or attitude at which the airplane is moving through the air.
- Some of these airplanes can do backflips, hover in the air with the nose pointed straight up, etc.
- The original experiments (X-31, HARV) used three paddles that could push the back of the airplane in any direction. However, most production applications only contain two paddles: each nozzle can only go “up” or “down”, like an elevon, no “rudder” authority. (At least some of the Sukhoi nozzles can only go “down and inwards” or “up and outwards”, so differential deflection gives both roll and yaw).
- Many VTOL jets also rely on thrust vectoring, not for maneuvering but for landing: X-13, Harrier, F-35 etc.

Contrails


B-17


DC-8


A340

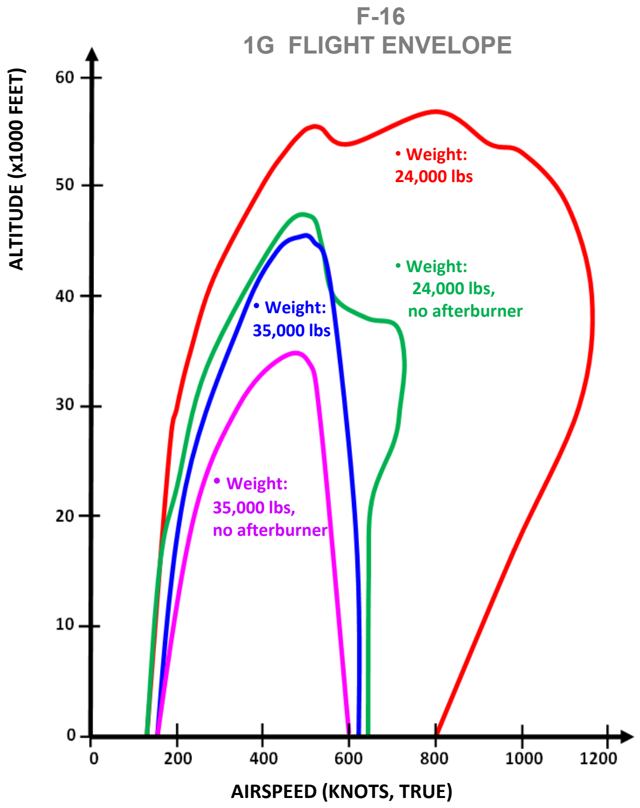

B-2

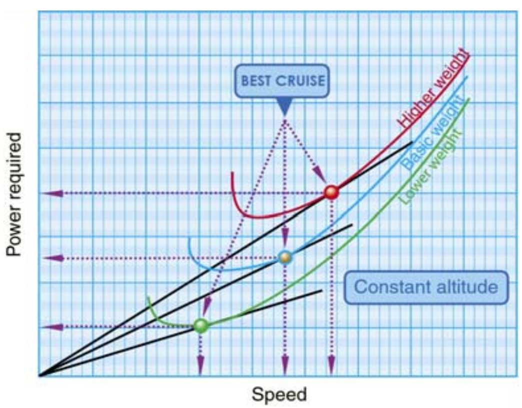

F-15s “intercept” MiG-29s coming to Abbotsford airshow, 1989

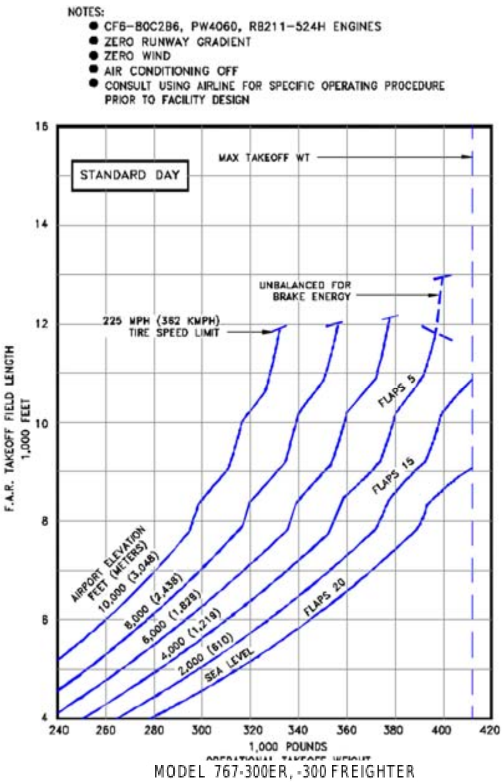
Contrails

- Engines that burn fossil fuels work with combustion reaction:
  [Fuel = some combination of C, H, sometimes O] + O_2 = CO_2 + H_2O
- Airplanes are surrounded by cold-air during high-altitude flight.
- Cold air can “hold” less water dissolved in it than warm air can.
- Instead of dissolving into the air, the water in exhaust might condense (similar to water in our breath during cold/humid days) and might form contrails. The water might then freeze.
- Between 30,000 and 40,000 feet, the air is typically both cold enough and humid enough to form contrails. (At over 40,000 feet: Too dry).
- The original B-2 design included tanks outboard of the main landing gear to hold chlorofluorosulphonic acid to mix with the exhaust and suppress contrail formation. This scheme wasn't actually used. Several chemicals were tested, but all were too corrosive. Instead, the B-2 carries an aft-facing Ophir LIDAR sensor to determine if it’s “conning”. It also often flies above 40,000 feet.

Performance





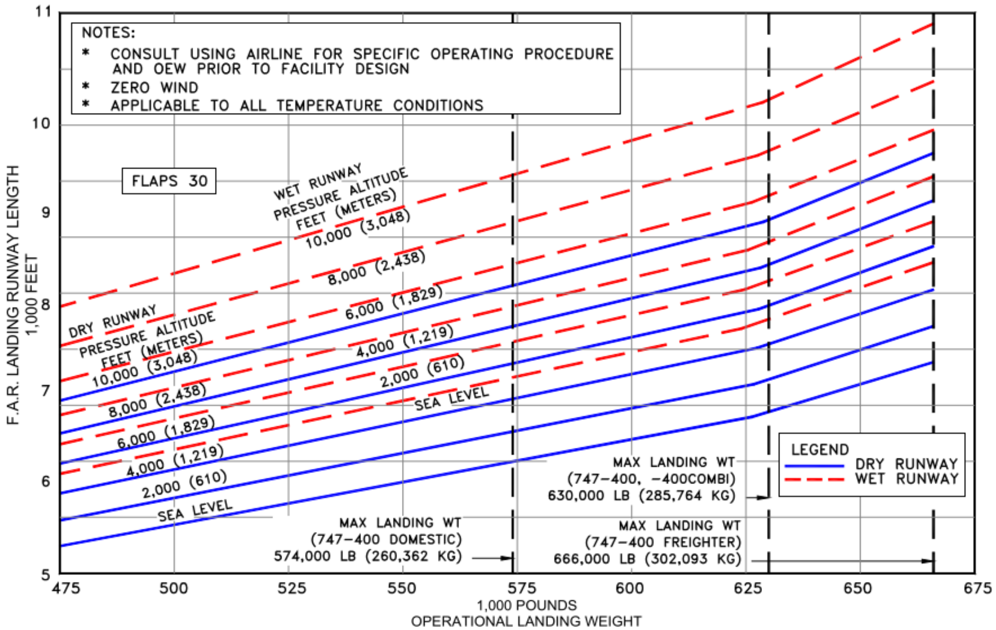


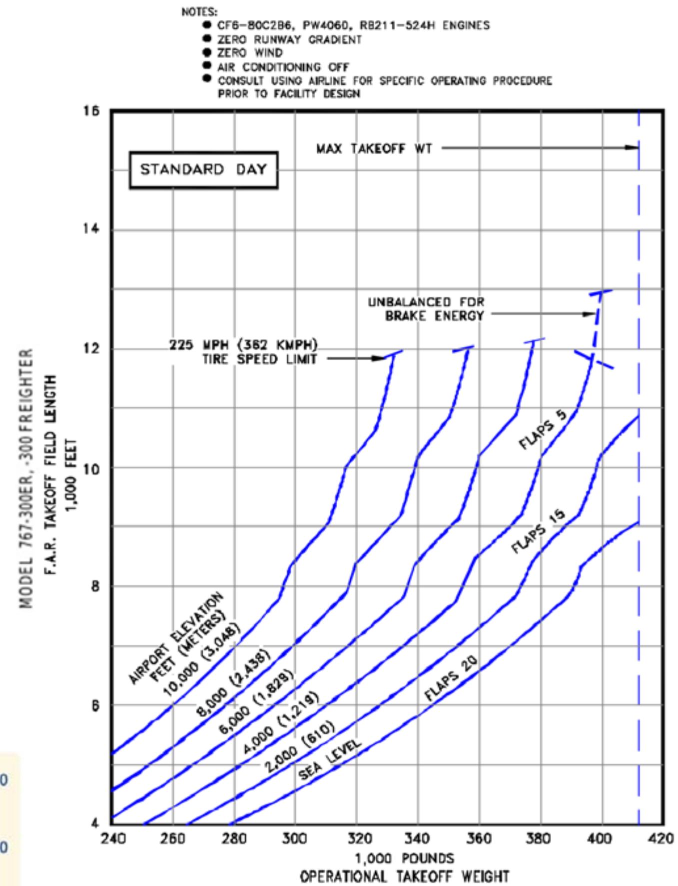
Performance

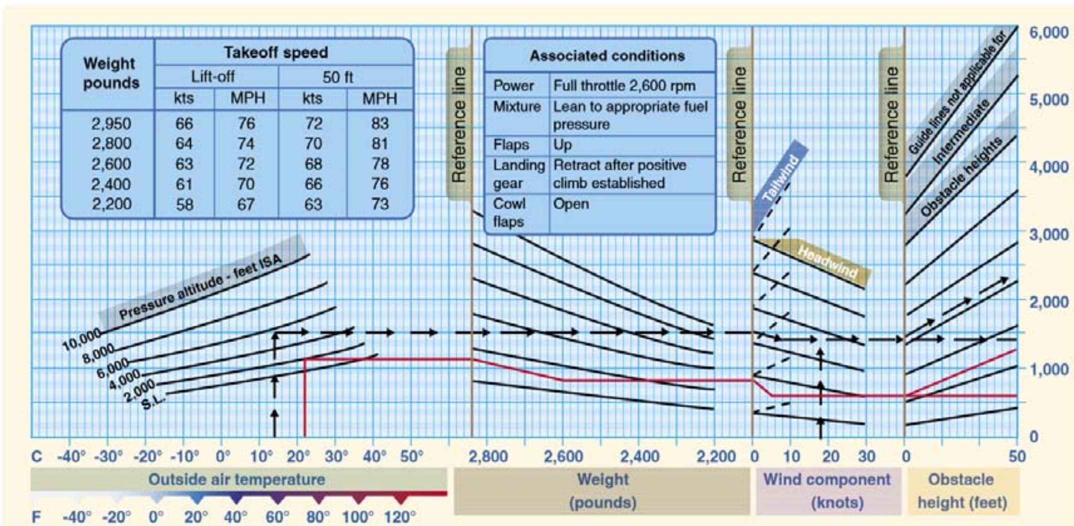
- How much weight could a given airplane possibly carry? How is this limited at some airports by runway length and air temperature and pressure?
- How much fuel can an airplane carry? How far can it fly as a function of its load?
- How much runway is required to take off? To land?
- How can we change the design to fly farther, carry more stuff, or be able to take off and land on shorter runways?
- What is the most fuel-efficient speed for a given airplane?
- How high can a given airplane fly?
- How steeply can an airplane climb? How far could it glide if it lost power?
- While designing a new airplane: How do we make sure that the airplane still operates safely if it loses an engine? Which requirements dictate the size of the wing, the size of the rudder, the height and location of the landing gear, the engine thrust, and where the engines are placed along the wingspan?

These questions are answered next. For each airplane, answering them typically means being familiar with a set of performance graphs: Not just *reading* the graphs, but understanding where their shape comes from and how it changes during flight (as a function of weight, altitude, etc.) and in modified designs (as a function of engine thrust, fuselage length, etc.).

Takeoff & Landing







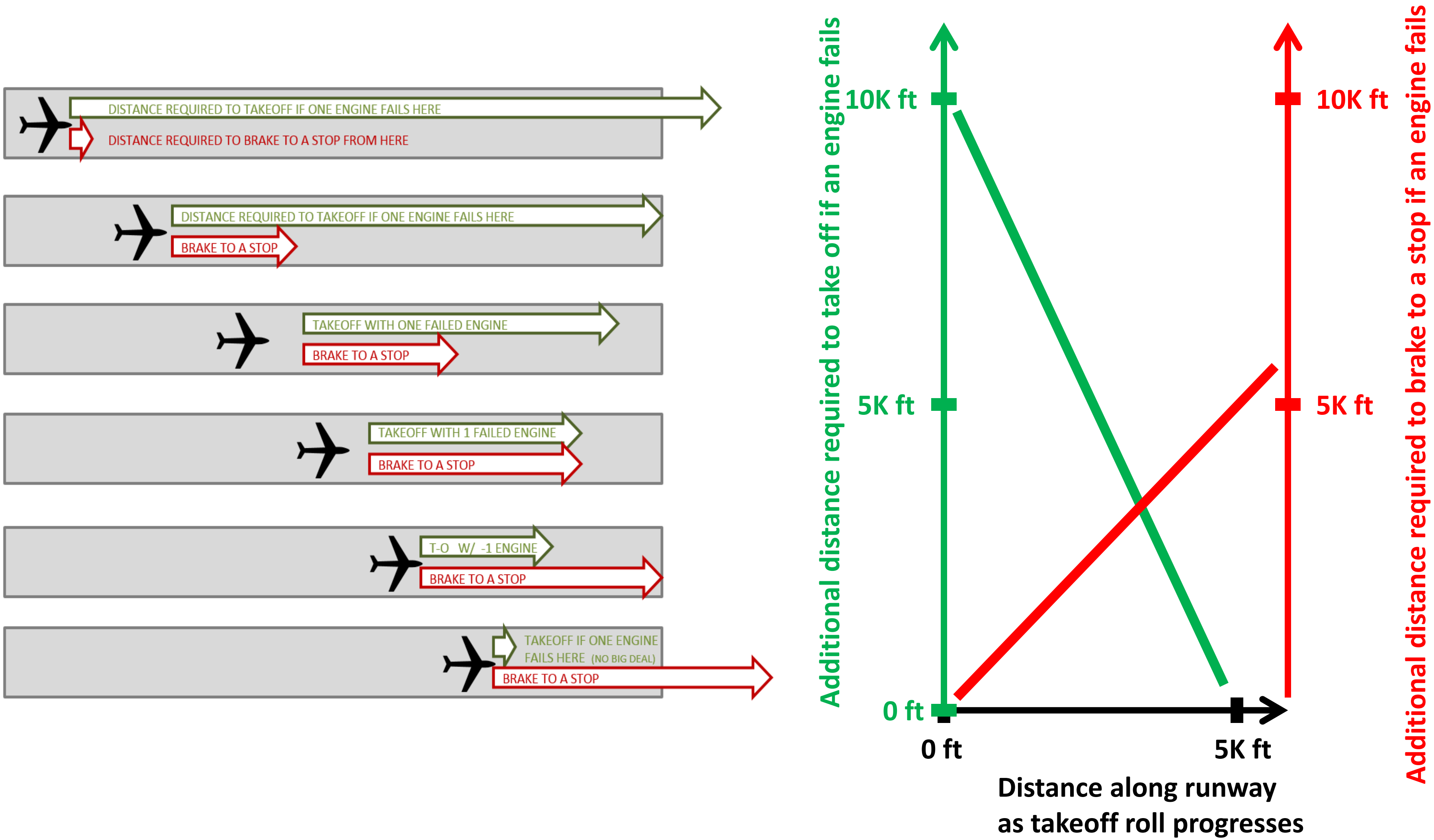
Airport and Runway Performance Limits					
YSSY		KLAX		PHNL	
RW 16R	37°C	RW 06L	314 T	RW 08L	330 T
RW 34L	36°C	RW 06R	345 T	RW 08R	347 T
OMAA		RW 07L	31°C	RW 26L	34°C
RW 13L	38°C	RW 07R	31°C	RW 26R	35°C
RW 13R	37°C	RW 24L	345 T	YMML	
RW 31L	38°C	RW 24R	327 T	RW 09	304 T
RW 31R	37°C	RW 25L	18°C	RW 16	35°C
YBBN		RW 25R	32°C	RW 16W/N8	293 T
RW 01	33°C	VTSP		RW 27	306 T
RW 19	34°C	RW 09	334 T	RW 34	32°C
		RW 27	346 T	RW 34W/N8	273 T
Blue = Highest temp that allow for Max TakeOff Weight					
Red = Max weight in Tons, if Temp is 15°C					

- In theory, takeoff & landing physics is simple: What is the takeoff speed (typically: the stall speed plus a safety factor like +15%)? How much time would it take to accelerate from rest to that speed (given the airplane's weight, the engines' thrust, and the wheels' rolling resistance and axle friction)? How much distance would this acceleration cover? Typically, we also ask: What if there is a 50-foot obstacle just across the street, i.e. How much ground would the airplane fly over while climbing from the group up to 50+ feet? That's all high-school physics: **f=ma** and **$x=v_o t+\frac{1}{2}at^2$** and so on. Pretty intuitive. Same thing for landing: The landing speed is the stall speed plus about 15%, the time (and thus the runway length) required to decelerate from that to rest depends on the airplane weight and on the tires' coefficient of friction given runway conditions, and the airplane could need to fly over a 50-foot obstacle just before touching down.
- In practice, airplane operating handbooks/manuals come with graphs that show how much runway is needed given the airplane weight an other factors, so that the pilots don't have to figure it out using physics equations.
- The impact of tailwinds/headwinds, runways that slope up or down, grass or wet or icy runways, airplane weight, air density (i.e. temperature and pressure, typically expressed as "density altitude" or "pressure altitude" i.e. the elevation where air has this density on a standard day), flaps setting, etc., are all quantified. They can either be shown as additional lines on the graph (e.g. the Boeing 747 graphs with additional dashed lines for wet runways, or the FAA nomogram in the previous slide, which is a notional example very similar to what is used on most single-engine airplanes), or as a correction factor (e.g. the Cessna 172 manual says "decrease landing distance 10% for each 9 knots of headwind"), or as a whole separate graph (e.g. Boeing has one graph for each flap setting that could be used during landing, e.g. "Flaps 30").
- Given a runway length and the air density, these sets of graphs allow the pilot to determine the max weight the airplane can take off at during the conditions at the time, or the max temperature and winds that would still allow them to take off with a certain weight.
- One 777 pilot has created this colorful cheat-sheet for the airports he flies into. The blue ones ("…°C") have enough runway for a max-weight takeoff on a standard day, but on hotter days, if the listed temperatures are reached, the 777's weight starts being limited. The red ones ("…T") have short runways, so on a "standard day" (15°C), these are the 777's weight limits there, and even less on hotter days. This pilot wrote an interesting article about one time when his flight was being delayed, and as the day got hotter, he had to decide whether to un-load things from his 777. It ended up depending on the wind. You can read his article at www.flight.org/performance-limited-takeoff-in-a-boeing-777
- During landing, it's ok for the airplane to be draggy. But during takeoff (and especially during climb, as we'll see), drag gets in the way. So steeper flap deflection settings are typically used on landing, and less steep flap deflections on takeoff. Also, the airplane is heavier on takeoff than during landing. For these two reasons (and due to the safety-margin, balanced-field-length reason we will discuss in the next slide), airplanes need more runway to take off than to land. If an airplane can take off from an airport, it can definitely land there. But it is physically possible to land at an airport where the runway is too short for safely taking off!
- Now, if you're designing an airplane, and you want it to have a certain weight (in order to carry the desired amount of payload plus enough fuel to fly the desired distance), engines with a certain amount of thrust, and wings with a certain coefficient of lift (i.e. flaps and slats with a certain level of complexity), then in order to take off from a runway of a certain length, you need at least a certain amount of wing area, enough for the airplane to lift off at the speed that it will achieve at that weight, with those engines, by the end of that runway.

In short, the wing area (i.e. overall size) on an airplane is primarily driven by takeoff and landing requirements

- Multi-engine airplanes (especially commercial transports) like to have an additional layer of safety during takeoff, so their takeoff requirements are a little more complicated.

Multi-Engine Takeoff



Multi-Engine Takeoff

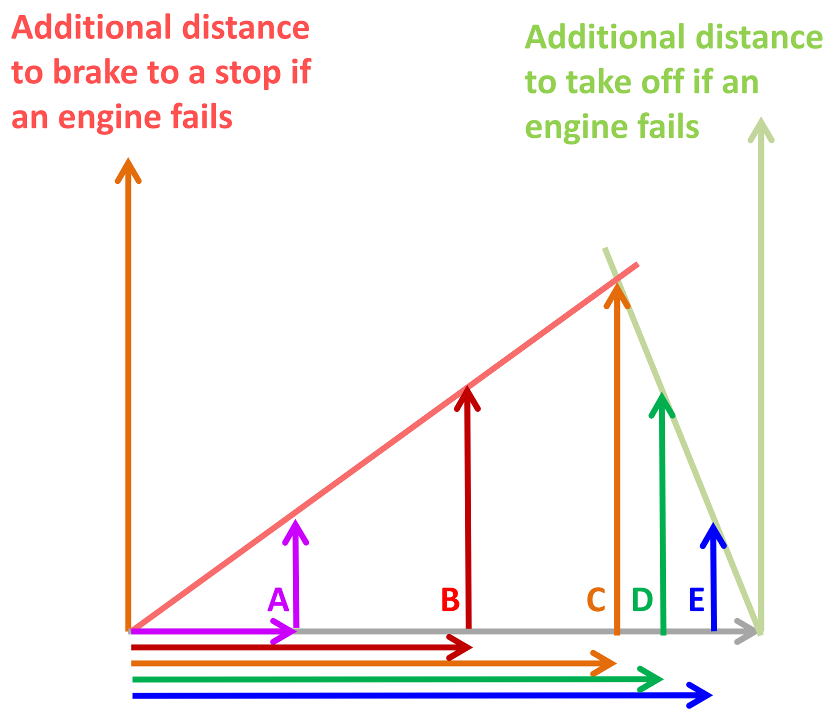
- There is some minimum distance that the airplane needs to barely get off the ground (as a function of air density and airplane weight) if both engines work flawlessly.
- If one engine fails, however: There is some ***longer*** distance that the airplane might need in order to abort a takeoff if the engine failure happens well into the takeoff, or to complete a takeoff with one engine failed. What is this longer distance?
- How do we make sure that, if an engine fails at ANY point during a takeoff, the airplane will not over-run the end of the runway (i.e. that it can either safely brake to a stop, or still reach take-off speed and lift off the ground, no matter when the engine fails)?
- When determining how much runway is needed for takeoff by a multi-engine airplane (or, rather, how much weight an airplane can take off with, given the runway and weather), the thought process goes something like this. Say that, for a given airplane weight and air density, if both engines work flawlessly, then I need 5000 feet to get off the ground. Say that the brake force is about the same as the engine force, and say that losing an engine would double the amount of runway needed to gain a certain amount of speed. Then…

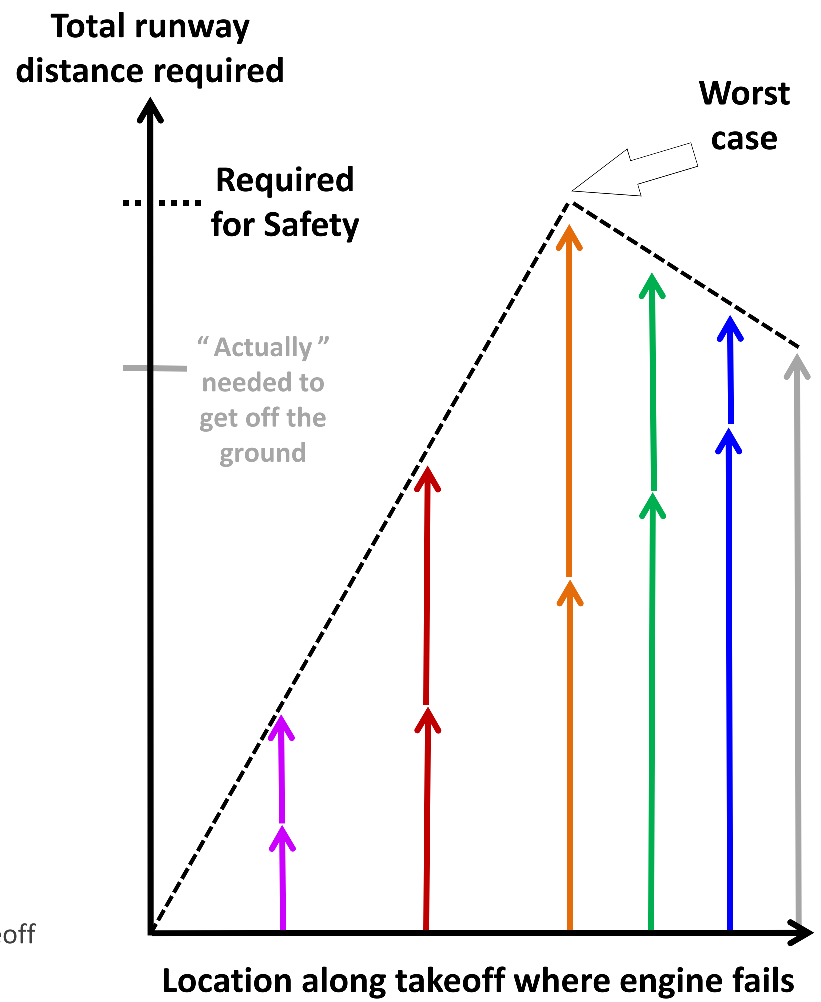
  - If I have an engine failure 500 feet down the runway: How much distance would I need to brake to a stop? About 500 feet more.
  How much distance would I need to accelerate to takeoff speed (with one dead engine)? about another 9000 feet.
  - If I have an engine failure 1000 feet down the runway: How much distance would I need to brake to a stop? Probably about 1000 feet more.
  How much distance would I need to accelerate to takeoff speed (with one dead engine)? Roughly another 8000 ft.
  - If an engine fails 1500 ft into the takeoff: About 1500 more ft needed to stop, or about 7000 more ft needed to complete the takeoff.
  - If an engine fails 2000 ft into the takeoff: About 2000 more ft needed to stop, or about 6000 more ft needed to complete the takeoff.

  …

  - If an engine fails 4500 ft into the takeoff: About 4500 more ft needed to stop, or about 1000 more ft needed to complete the takeoff.
  - If an engine fails 5000 ft into the takeoff: About 5000 more ft needed to stop, or about 0 more ft needed to complete the takeoff.
- At the beginning of the takeoff, braking to a stop would be quick and ***not*** require a lot of runway. Completing the takeoff with one engine failed, however would take a ***LOT*** of additional runway.
- Near the end of the takeoff, when the airplane is almost at takeoff speed, completing the takeoff with one engine failed would be quick and ***not*** require a lot of extra runway. Braking to a stop, however would take a ***LOT*** of additional runway.
- What is the worst-case scenario? Of all the places where an engine would fail, which would require the most ***total*** runway?

Multi-Engine Takeoff



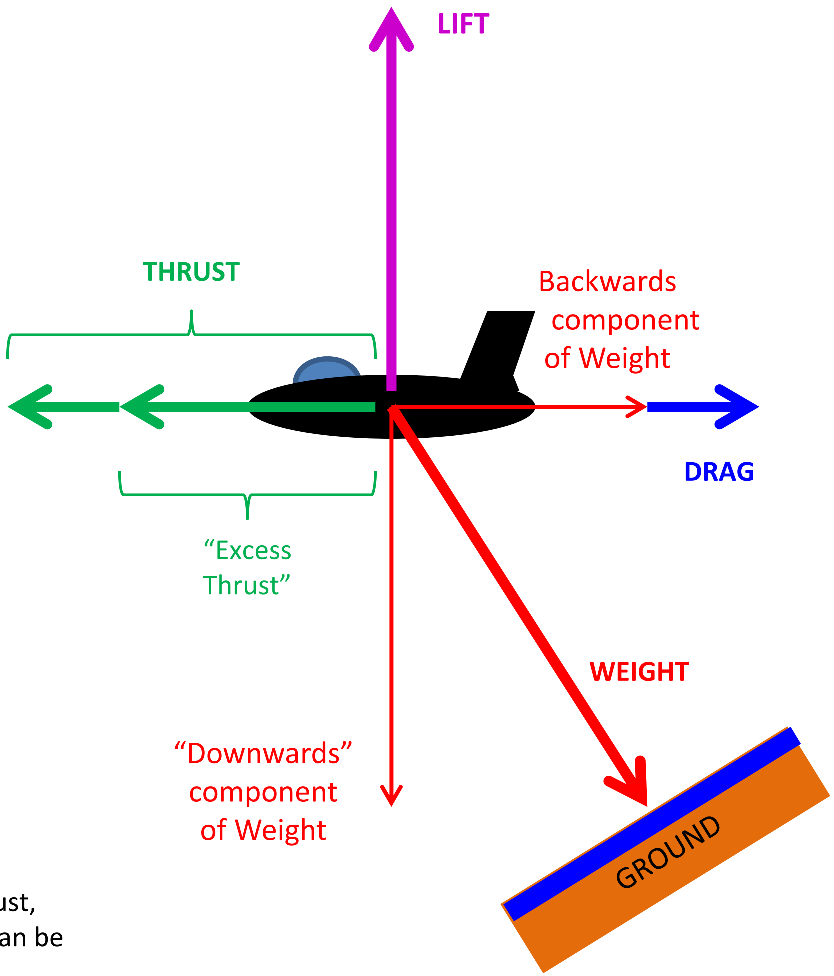


How much total runway is needed for…

- Engine failure at **A**, plus distance required to stop
- Engine failure at **B**, plus distance required to stop
- Engine failure at **C**, plus distance required to stop OR to complete the takeoff
- Engine failure at **D**, plus distance required to complete the takeoff
- Engine failure at **E**, plus distance required to complete the takeoff
- No engine failure

- What's the worst-case scenario? Of all the places where an engine would fail, which would require the ***most*** total runway?
- As you can see by the graphs (and from the arrows in slide 296): The worst case is an engine failure at the point where the distance required to come to a stop is the same as the distance required to complete the takeoff with one engine failed (here called "C").
  - If the engine fails any earlier, braking takes less extra runway, and less total runway is required.
  - If the engine fails any later, completing the takeoff requires less extra runway, and less total runway is required.
- If the airplane has enough runway to make it to this critical point (where braking ***or*** completing the takeoff would require the same additional runway), to then experience an engine failure, and to then brake to a stop or complete the takeoff… this means that, no matter where the engine failure occurs, the airplane will not run off the end of the runway.
  - If an engine fails before this point, the airplane has enough room to brake to a stop.
  - If an engine fails after this point, the airplane has enough room to reach takeoff speed on one fewer engine (which takes more time i.e. requires more runway than if all engines were working).
  - If the runway were any shorter, then an engine failure at or near that critical point would mean the airplane would not be able to come to a stop, ***or*** get off the ground, before the end of the runway ☹
- This is known as a ***balanced field length;*** the minimum runway length required for a safe takeoff in a commercial airplane.
- How much longer is this "safe" runway length, compared to the runway actually required just to get off the ground? Depends on things like the ratio of the engine thrust to the tire traction (e.g. for an F-22 [which accelerates in a short distance] or for a wet runway, that red line would go up much more steeply), and how many engines the airplane has (e.g. if it has 4 engines instead of 2, then taking off with one fewer engine would not prolong the takeoff roll that much, so that green line would come down less steeply from a max value that is less high). Assuming that the acceleration with one engine is ½ the acceleration with two engines (actually it's less, because drag and rolling resistance do not drop to ½ if an engine fails) and that the braking deceleration is the same as the max-thrust acceleration (which actually depends on how over-powered the airplane is, whether the runway is wet or icy, etc.), you can do algebra on the graphs (the green line is $y=-2(x-1)$, the red line is $y=x$, they meet at some $[x_1,y_1]$, the total required runway is x_1+y_1): In order to prevent an over-run in case of an engine failure anywhere, you require ***over one third more runway*** than what the airplane "actually" needs to get off the ground. In other words, according to this slightly-simplified linear analysis: If you take the required runway length for a given flight (i.e. a given airplane, weight, and air density), over one quarter of that required runway length is there "just in case", and will almost certainly not actually be needed. (I say "over" because the green line is actually steeper than shown here, due to drag and rolling resistance).
- With more engines (e.g. four), you'd need less buffer: If the green line has a slope of -4/3 instead of -2 (i.e. assuming that an engine failure causes you to have ¾ as much acceleration, rather than only ½ as much acceleration), the buffer drops from 33% "extra" runway to 14% "extra" runway. So, because it has four engines, the 747 is allowed to take off with much less buffer, i.e. to actually used up nearly all the runway at the airport, without requiring as much "extra" runway "just in case". Losing one engine in a 747 is much less bad than in a twin!

Climbing

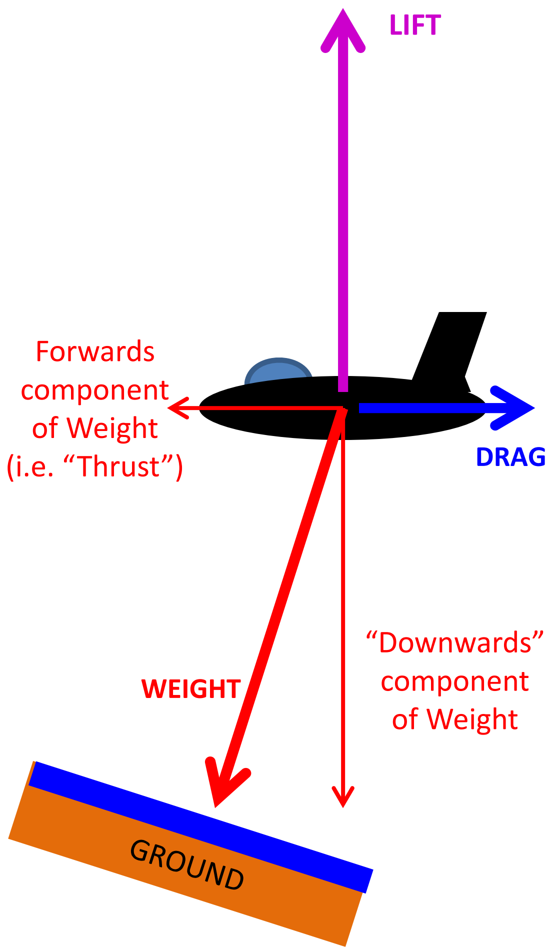


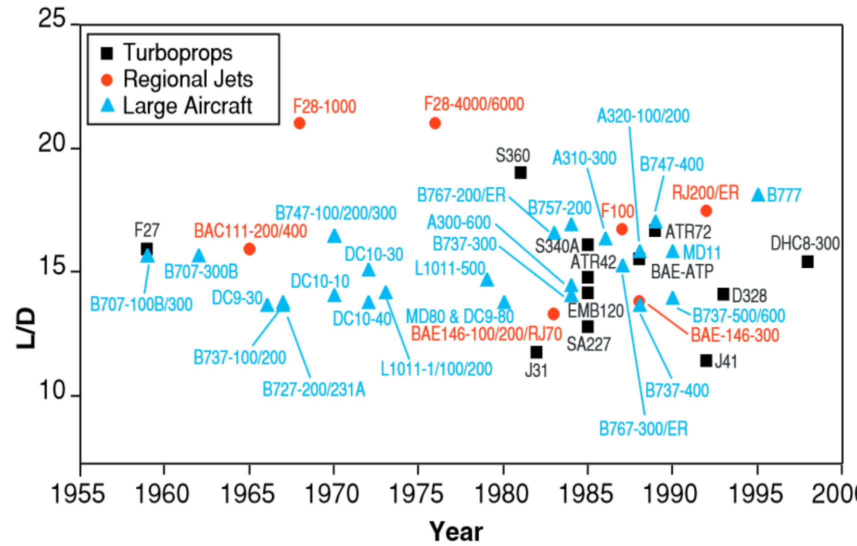
The more excess thrust,
the steeper the climb can be

Thrust-to-Weight Ratio

- **How quickly will an airplane accelerate during the takeoff**? Depends on its **Thrust-to-Weight ratio**, T/W (and on the increase in air resistance and wheel rolling resistance, which subtract from the thrust as the airplane picks up speed). So the takeoff speed and the T/W determine how long the takeoff roll will be.
- **How steeply can an airplane climb?** Depends on the ***Excess*-Thrust-to-Weight ratio**, where "*excess* thrust" is how much thrust the engines can generate, minus the thrust that is required to fly at the speed that the airplane is at, i.e. minus the drag. So, you climb while flying at your minimum-drag speed; That way, you have the most thrust "left over" for climbing. Same physics as a car or bicycle going uphill. The more overpowered the airplane (i.e. the more excess thrust it has), the more steeply it can climb.
- (In airplanes other than airliners, the T/W ratio is also crucial for things like aerobatics and dogfighting, in determining how much speed is lost during vertical maneuvers and during high-alpha maneuvers such as tight turns.
The more excess thrust, the more sustained Gs can be pulled,
because the more induced drag can be overcome without the airplane slowing down).
- Note that, during steady level flight, Thrust=Drag and Lift=Weight.
So it seems like T/W=L/D , the *Lift-to-Drag* ratio.
This is not quite right, however, because T/W usually means the ***max*** thrust,
while L/D usually uses the ***minimum*** drag or the drag at cruise.

L/D and the Glide Ratio

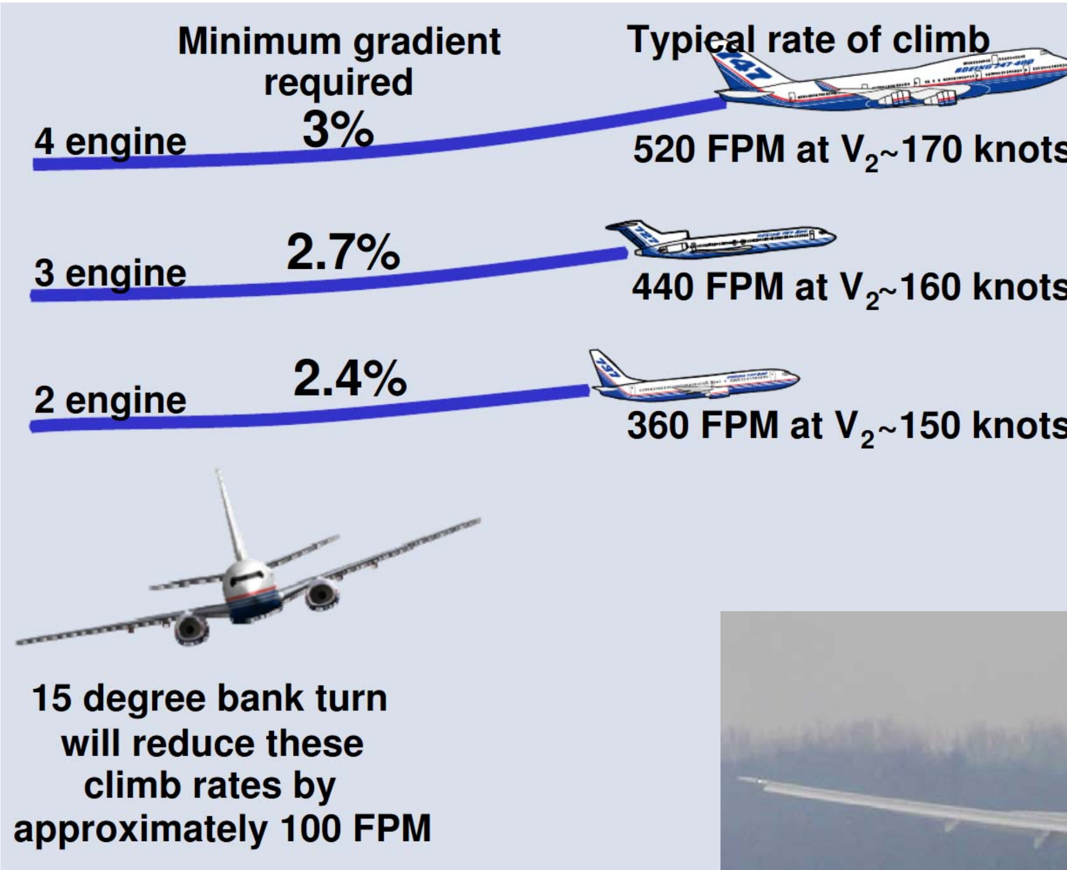




L/D and the Glide Ratio

- The **Lift-to-Drag ratio** during cruise flight is a common way to measure aerodynamic efficiency. It answers a fundamental question about the airplane (or, sometimes, only about its wing): ***To carry this amount of weight*** (i.e. to generate this amount of lift) ***at this speed, how much drag do we need to overcome?*** (i.e. how hard do the engines have to work?)
- (You can see why some aerodynamicists are obsessed with flying wings: Fuselages are all "D", no "L"!)
- Most of the advance in jetliner aerodynamics over the past several decades can be summarized by their increasing L/D: **13** to **15** in the 727/DC-10 days, **18** to **21** now. That's almost 50% better! To cruise, a modern jetliner only needs about 2/3 as much thrust as an old one of the same weight!
  (Data from http://web.mit.edu/aeroastro/sites/waitz/publications/Babikian.pdf and http://aviation.stackexchange.com/questions/1738/how-does-the-boeing-787-dreamliners-glide-ratio-compare-to-other-airliners)
  Supersonic and single-engine airplanes L/D are around 8-12, sailplane gliders are over 30, the Space Shuttle L/D was around 4.5, wingsuits achieve an L/D of about 2.5.
- **How far can an airplane glide if it loses all power?** How "shallow" can the glide be? From the pilot's point of view (flying slightly downwards rather than horizontally), the weight has a slightly forwards component that acts like thrust.
- Steady gliding flight is achieved when the ratio of "downwards weight" (the component of weight perpendicular to the airplane's belly) and "forwards weight" (the component pulling in the direction out the nose) matches the ratio between lift and drag (which oppose those two components of the weight). [This is done every day in gliders, and occasionally in jets ☹].
- So **the glide ratio** (number of feet flown forwards for every foot flown downwards) **is the same as the L/D ratio**! So if you lose all your engine power, slow down to your minimum-drag speed, to maximize your gliding range by maximizing the L/D.

Engine-Out Requirements



(If your rudder is big enough, then even in an engine-out, you should be able to fly straight forward, without the kind of crabbing or sideslip implied by this photo).

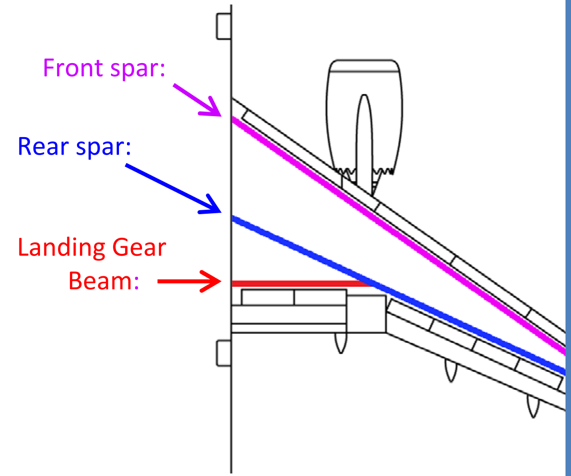
777 FIGHTING A CROSSWIND

Engine-Out Requirements

- Multi-engine airplanes such as commercial airliners have to be able to **fly with one engine failed**. And not just “fly” but **take off, climb slightly, set up an approach, and land**.
- Note that the requirements are for performance with ONE engine failed. So for a four-engine airplane, this means flight at ~75% power. For a twin-engine airplane, it means flight at ~50% power. So **twin-engine airplanes tend to be more over-powered than four-engine airplanes,** because they have to be able to lose HALF their thrust and still do all this (although the engine-out climb requirement is slightly easier on twins than on quads).
- These requirement drive a lot of things, such as choosing the required **thrust of the engines**, and the required **size of the rudder** for a new design, and (as we saw) determining the required **runway length** for an existing airplane .
- As we saw, the **rate of climb and angle of climb** depend on the **“excess thrust”**, i.e. thrust in addition to the thrust that would be needed to fly at that speed in level flight. If an airplane of a certain weight must be able to climb at a certain angle (and generates a certain amount of drag), then **this sets the minimum engine thrust required for that airplane**.
- Imagine you are at an airport with a very long runway, and at high elevation on a hot day, i.e. the air density is low, so the engines cannot generate as much thrust. On such occasions, the climb-out requirements might limit the airplane’s maximum weight for that takeoff, rather than the runway length or the airplane structure. But if the runway is long enough, **the pilot may be able to increase the takeoff weigh by using less flaps/slats**. **Flaps/slats add lift** (which reduces the takeoff speed and thus the required runway length) **but they also add drag** (and thus reduce the excess thrust and the climb angle). So by reducing flap/slat deflection on takeoff, the required runway goes up, but the climb angle gets better, i.e. the airplane can take off with more weight and still meet the climb requirements… as long as the runway is long enough and the tires can take the extra speed on the ground. (Notice how, due to this reasoning, pilots typically use full flaps/slats deflection for landing, but less deflection for takeoff).
- **Rudder size**: The airplane flies the most slowly right after takeoff and during the approach to land. This means that those times see the lowest dynamic pressure, and the lowest forces (i.e. most sluggish behavior) exerted by any given control surface… such as the rudder. If one engine fails, the rudder needs to exert enough force to overcome the asymmetric thrust. This can be especially difficult right after takeoff, or during an aborted landing (go-around), because that is when the engines are generating the most thrust. **This condition determines how big the rudder must be**: The further outboard the engines are, the higher the thrust asymmetry will be, and the larger the rudder has to be in order to be able to overcome that asymmetry and keep the aiplane flying straight even at slow speeds and max power. (If the engines could be on the centerline, like a Cessna Skymaster, or very close like in a Beech Starship, then the rudder could be tiny). On the other hand, the further outboard the engines are, the less bending is caused on the wing by lift (because some of this bending is un-done by the engine weight), and the thinner the wing structure can be. **The engines end up at the optimal location that minimizes the *total* drag, from the rudder size *plus* from the weight of the wing structure.**

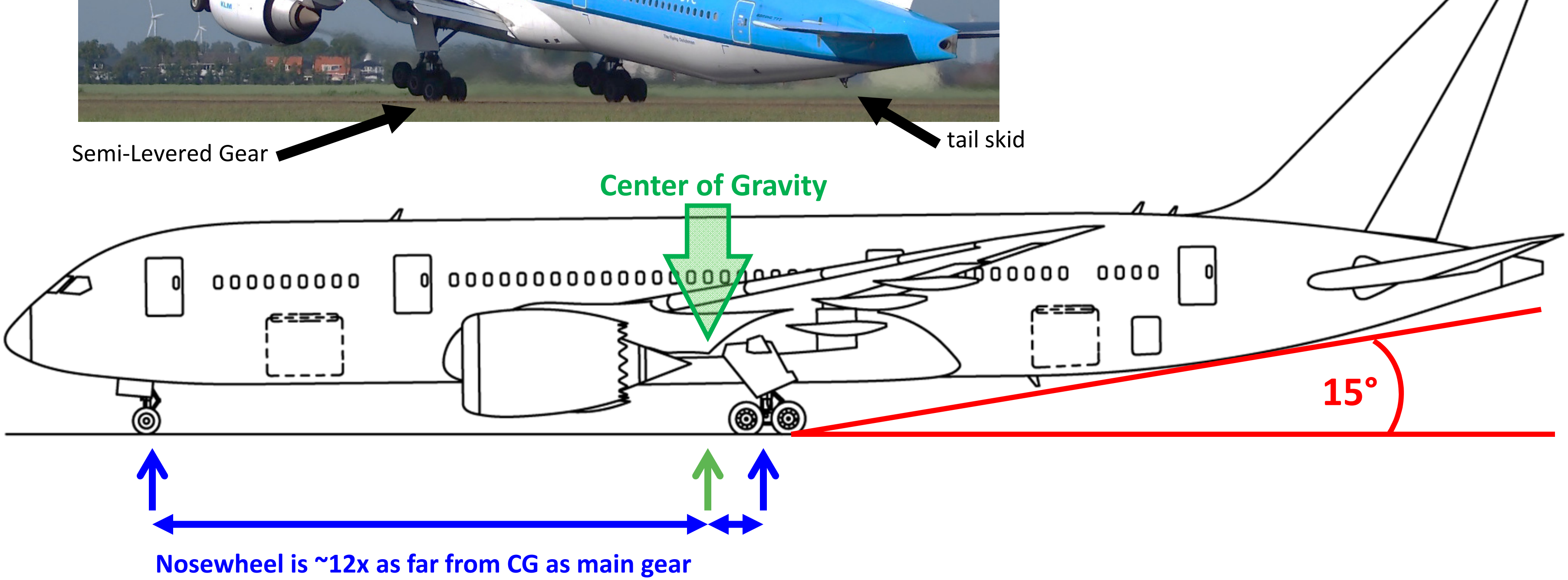
Landing Gear

Hurricane season in Florida:



Semi-Levered Gear

tail skid



How far back should the landing gear be along the fuselage?

- One might answer: "Right under the center of gravity. That way, it will be easy for the elevator to push the tail down during takeoff, and the nose won't come slamming down on landing". However… three problems:
  - One: If the rear of the airplane is loaded first, or if the engines are removed without the airplane being properly secured, or if a strong gust blows… the airplane could end up sitting on its tail. (This already happens once in a while, as it is).
  - Two: While taxiing, the airplane is steered by the nosewheel. The nosewheel needs some force pushing it down into the ground, otherwise it would have no traction and would skid when turned.
  - Three: If the engines are very low (as they typically are on airliners), the nose-up moment from full thrust at takeoff will reduce nosewheel traction (and might even lift it off the ground) at the beginning of the takeoff roll when the airplane does not have enough airspeed to be controllable by the rudder. The airplane would have no steering for the first several seconds, if at full power.
- For these reasons, typically, the nose gear is placed so that the distance from the CG to the nose gear is ~12x greater than the distance between the CG and the main gear. This way **the nose gear takes~8% of the airplane's weight**. (Depending on whether the CG is near the front or the back of the permissible envelope, the nose gear will typically take 5% to 10% of the weight, but it can be as little as 3% [1, page 98] and as much as 12% [2, page 374]).

1: http://www.boeing.com/assets/pdf/commercial/airports/acaps/747_8.pdf
2: http://www.airbus.com/fileadmin/media_gallery/files/tech_data/AC/Airbus-AC-A340-500-600-20140101.pdf
3: http://www.boeing.com/commercial/aeromagazine/articles/qtr_1_07/article_02_5.html
4: http://www.google.com/patents/US6182925

- Recall that you want the CG near the leading edge of the wing (i.e. ahead of the center of lift). So, on airplanes with straight (unswept) wings, it usually works out well to place the main gear near the trailing edge of the wing (i.e. just behind the center of gravity), e.g. on the rear spar. With swept wings (e.g. on modern jetliners), however, this gets a little trickier: The inboard part of the wing is further forward than it would be if the wings were straight, so the rear spar is just a bit too far forwards, too close to the CG. The solution? Add an unswept segment to the inboard part of the trailing edge (known as the Yehudi), and put a spanwise beam through it for the landing gear, like a bridge between the rear spar and the fuselage. (The landing gear beam is not perfectly spanwise as shown here, usually it's at a slight angle). [Note: the Yehudi is sometimes accompanied by a "glove", i.e. a region right by the fuselage where the leading edge is more steeply swept; The LongEZ's strake is an extreme example. Yehudis, and gloves on airplanes that have them, bring advantages in addition to the ability to mount the landing gear in the best place: Given some airfoil shape, increasing the chord also increases the thickness, so the wing can be thicker/taller where it meets the fuselage, (A) reducing the bending forces at the side-of-body and allowing for the gear – and more fuel – to more easily fit in the wing. In addition, (B) swept wings naturally make less lift in the region where they meet the fuselage, causing a "valley" in that optimal elliptical lift distribution that we want along the span. Increasing the chord at the wing root reduces this problem].

How tall should the landing gear be?

- Most airliners stall at a little over 15˚ alpha. So the pilot should be able to pull up to almost 15˚ on takeoff without the tail hitting the ground. And engines must have so-much ground clearance, even when the airplane lands at a slight bank angle. The landing gear must have enough height to allow for this.
- This has implications for stretching derivatives. Re-designing the main landing gear to be taller is almost always prohibitively difficult (with very rare examples like the 737-MAX10). The longer an airplane is (without the landing gear getting any taller), the lower the rotation angle on takeoff that would cause a tail-strike (so the more likely a tail-strike becomes). The more "extra tall" the landing gear is on a new model, the more easily this new model can be stretched later. (E.g. The DC-8 could be stretched to bigger sizes than the 707 because the DC-8 had taller landing gear). And notice how longer derivatives (e.g. the 737-900, 777-300, etc.) often get tail skids / tail-strike sensors.
- Some airplanes [3] have Semi-Levered Gear [4], "SLG". An additional hydraulic piston "locks up" the wheel truck, so that when the airplane rotates on takeoff, it pivots about the rear wheels (like standing on your tippy-toes, except for how the wheels point aft). This allows for more α (i.e. more lift) before getting too close to a tail-strike, without the gear needing to be extra tall.

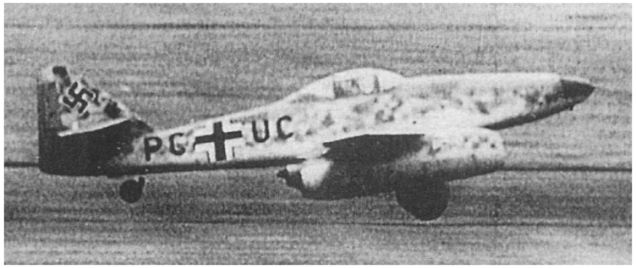
Tail-draggers

DC-3

DHC-2 Beaver

U-2

T-6 and PT-17 ground loops



Me-262 prototype

RV-7A “pole vault”

Tailwheel airplanes were ubiquitous until the late 1940s. (The technical term for this arrangement is still “conventional landing gear” as opposed to “tricycle landing gear”). What are their pros and cons?

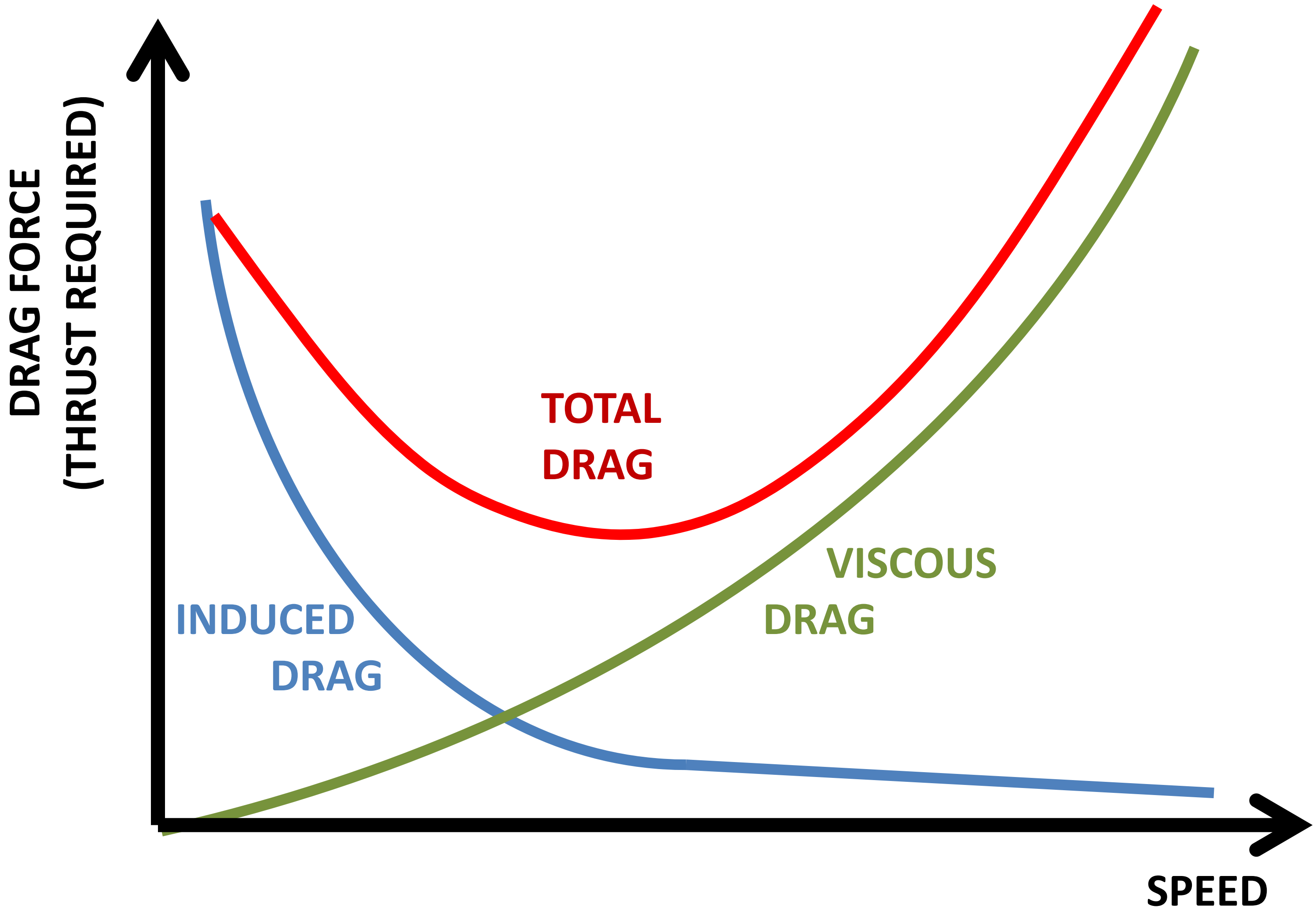
Advantages

- The taildragger’s key advantage is that, on rough terrain, nosewheels have a propensity to “catch” bumps on the ground. Either the nosewheel breaks and the airplane ends up sliding on its nose, or the airplane flips over its nose (“pole-vaults”) and ends up on its back. So **for landing on unpaved runways, and definitely for landing in the wilderness, taildraggers are preferable. Most bushplanes are taildraggers. Before World War 2, there were not many long paved runways, also favoring taildraggers** as airliners and fighters. (Many nosewheel airplanes were introduced during World War 2 such as the B-24, B-29, P-38, P-61, P-63, F7F, and Constellation).
- One may guess that the nose-up angle allows for a bigger and thus more efficient propeller. However, this is not really the case: Much of the takeoff, and sometimes the landing, is performed in a conventional horizontal orientation with the tail in the air (rather than a “three point” pitch attitude with all wheels on the ground). A minimum-distance landing is actually performed with a slight nose-down attitude, so that the wings generate downwards lift to help with wheel braking. For these reasons, the propellers may not be larger than for a tricycle-gear airplanes, unless the landing gear is taller.

Disadvantages

- The takeoff roll is slightly longer than for an otherwise-identical nosewheel airplane, because the direction of the thrust is (at least initially) partially upwards, giving the thrust a slightly reduced horizontal component.
- Hit the brakes too hard and the nose – or worse, the prop – might hit the ground.
- **Taildraggers are unstable in yaw whenever the wheels are on the ground**, i.e. during taxi, takeoff, and landing. (Because of this, flying taildraggers requires a special endorsement). This is because the main gear is ahead of the CG, so a taildragger on the ground is like a bicycle being pushed backwards by the handle-bars: Any slight angle to the side will trigger a force that pushes it even further to the side. (The extreme of this is the “ground loop”, where a taildragger veers sharply to the side, typically causing one wingtip to hit the ground). A pilot controlling a taildragger during taxi, takeoff, and landing has his/her feet on the rudder pedals at all times, always pushing slightly this way or that in order to keep the airplane going in a straight line.

Power Curve. Best speeds?



Power Curve. Best speeds?

- What is the most fuel-efficient speeds for a given airplane?
- Depends on the shape of its *power curve*:
- Viscous drag experienced by all airplanes, and compressibility drag and pressure drag experienced by some airplanes, gets worse at higher speeds.
- Induced drag gets worse at lower speeds.
- Plot them on a graph and add them up, and you get what is known as the *power curve* for a given airplane.
- The left region, known as "the back of the power curve", is tricky: Speed is unstable! Slow down, and your drag increases, which slows you more, which increases the drag… In other words, while flying slowly, keep an eye on the airspeed! If it starts to drop, don't let it drop too fast! Add power and lower the nose right away! You're walking on a tight-rope!

Say I give you some fuel-burn rates:

RV8
75 mph
5 gph

RV8
140 mph
6 gph

RV8
180 mph
12 gph

172
60 mph
5 gph

172
90 mph
6 gph

172
100 mph
8.3 gph

205
60 mph
6.6 gph

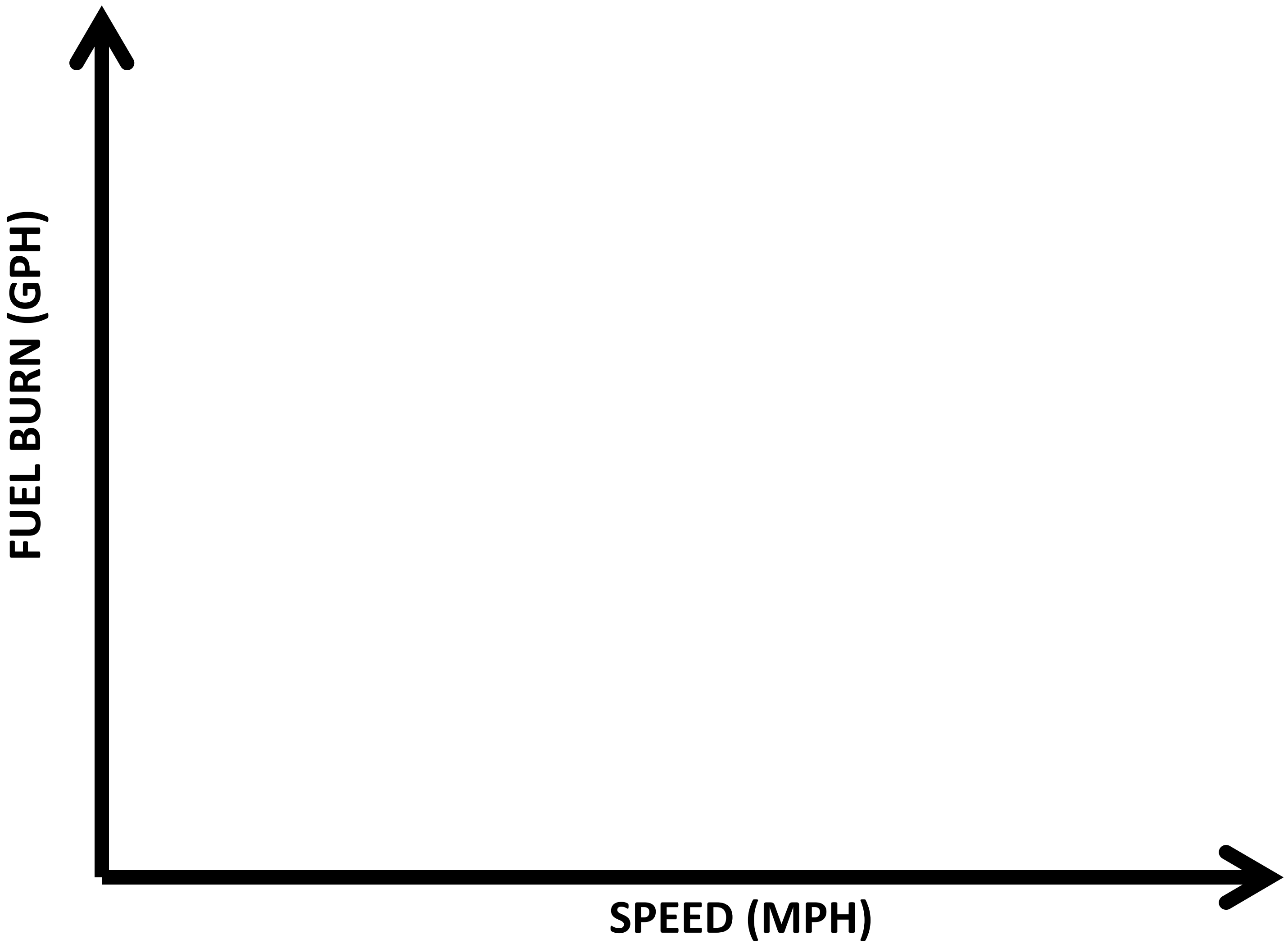
205
90 mph
7.5 gph

Best speeds?

- The next step in figuring out the most fuel-efficient speed for a given airplane requires learning to think about miles-per-gallon (MPG) in a certain way.
- Here are some examples of combinations of gallons-per-hour and miles-per-hour, for three airplanes. The Cessna 205 flies at similar speeds to the Cessna 172, but the 205 is bigger (and has a bigger engine), so it will burn more fuel for each speed than the 172. The RV-8 has the same engine as the 172, but it's a smaller airplane, so for some given power setting on the engine (e.g. for a given rate of fuel burn), the RV-8 will fly faster than the 172.
- (These numbers are not exactly right; I fudged them a little bit to make the trends clear. But they're in the right ballpark. Not to mention, the relationship between fuel burn and speed changes with altitude, generally getting better as you fly higher).
- Bur for now, don't even worry about what airplane each of the eight boxes comes from. Just think about them as eight combinations of speed and fuel burn rate.

- Note: In general, bigger airplanes will burn more GPH for a given speed, and smaller airplanes can go faster for a given fuel burn. We could have done this exercise with a Gulfstream 650, a LearJet, and a T-38, for example. More ballpark numbers: Large airliners will do 550 mph while burning roughly 3000 to 5000 GPH. Business jets do ~400 mph while burning 100-200 GPH, as little as 65 GPH for the smallest bizjets. An 86-foot yacht might cruise at 22 mph while burning 110 GPH. Two 2000-ton locomotives will go at 40 to 70 mph (depending on incline/gradient) while burning 250 GPH. (That's about the same MPG as a 767 or A330, but carrying 40 to 80 times the payload).

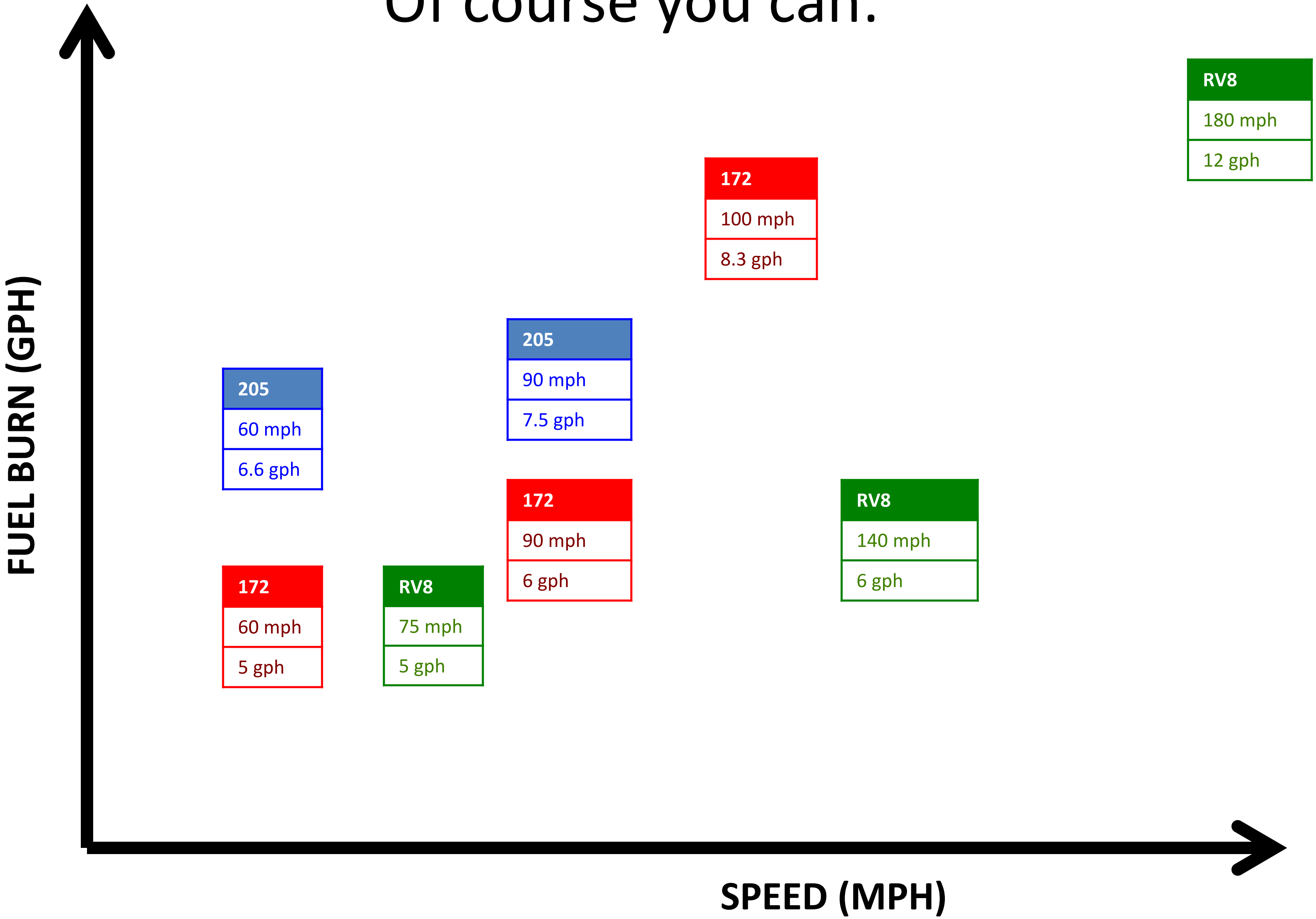
Can you place them between these two axes?



Best speeds?

- Look at the eight boxes in slide 312. Can you place them on these axes?
- The faster the fuel burn rate, the higher up each box will be.
- The faster the speed, the further to the right each box will be.

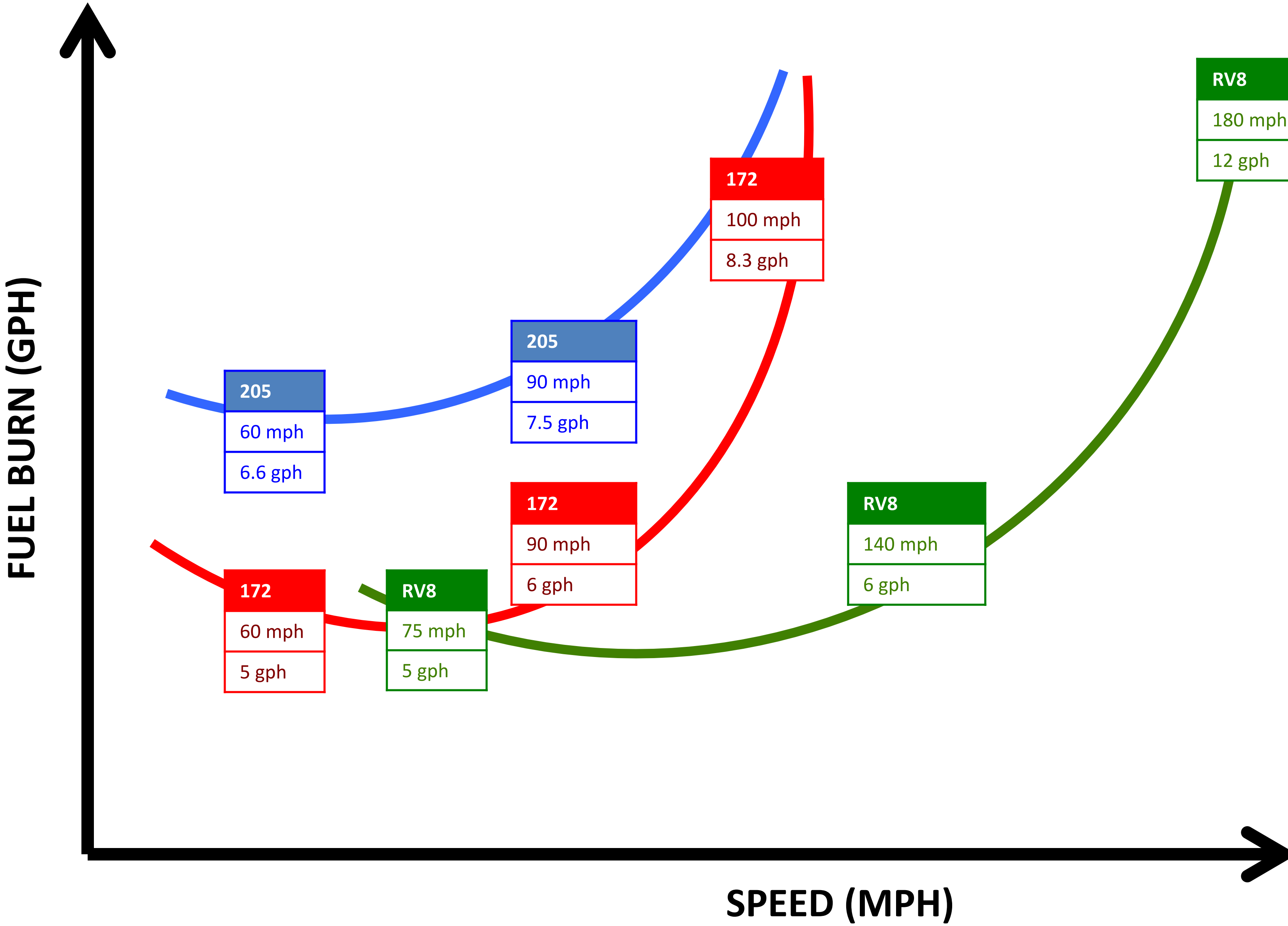
Of course you can:



Best speeds?

- It is not difficult to arrange those boxes in this diagram.
- The faster the fuel burn rate, the higher up each box will be.
- The faster the speed, the further to the right each box will be.
- This may seem trivial, but bear with me, there is an interesting insight ahead!

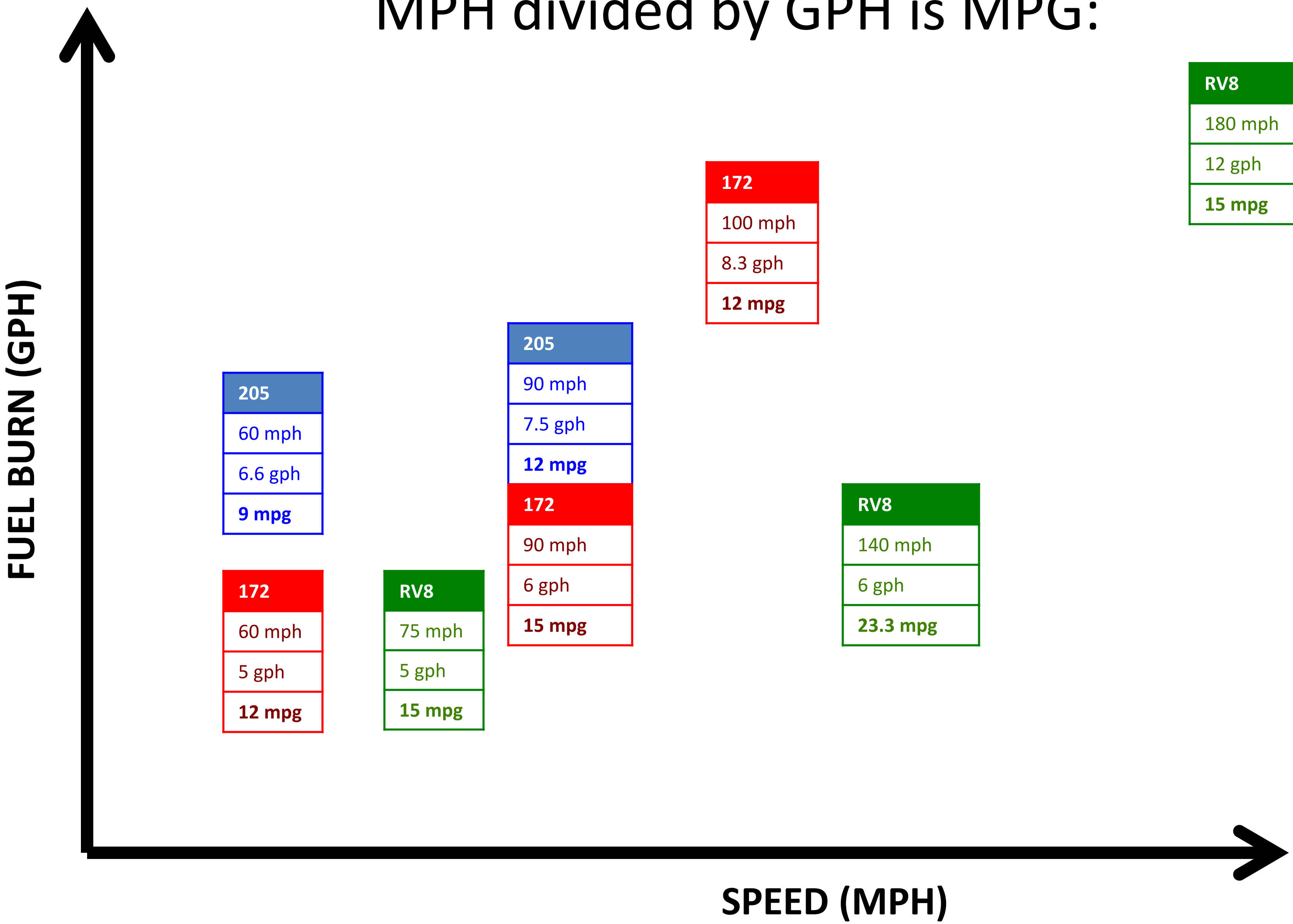
Remember that each airplane has a power curve:



Best speeds?

- As a quick aside, if we do remember that these boxes can be grouped into three airplanes, each at various speeds and power settings, we can start to see how each airplane has a different power curve.
- But for the next step, do try to forget that these boxes can be grouped into three airplanes. Just think of them as eight combinations of speed and fuel burn rate.

MPH divided by GPH is MPG:



Best speeds?

- If you think about it, you will realize that

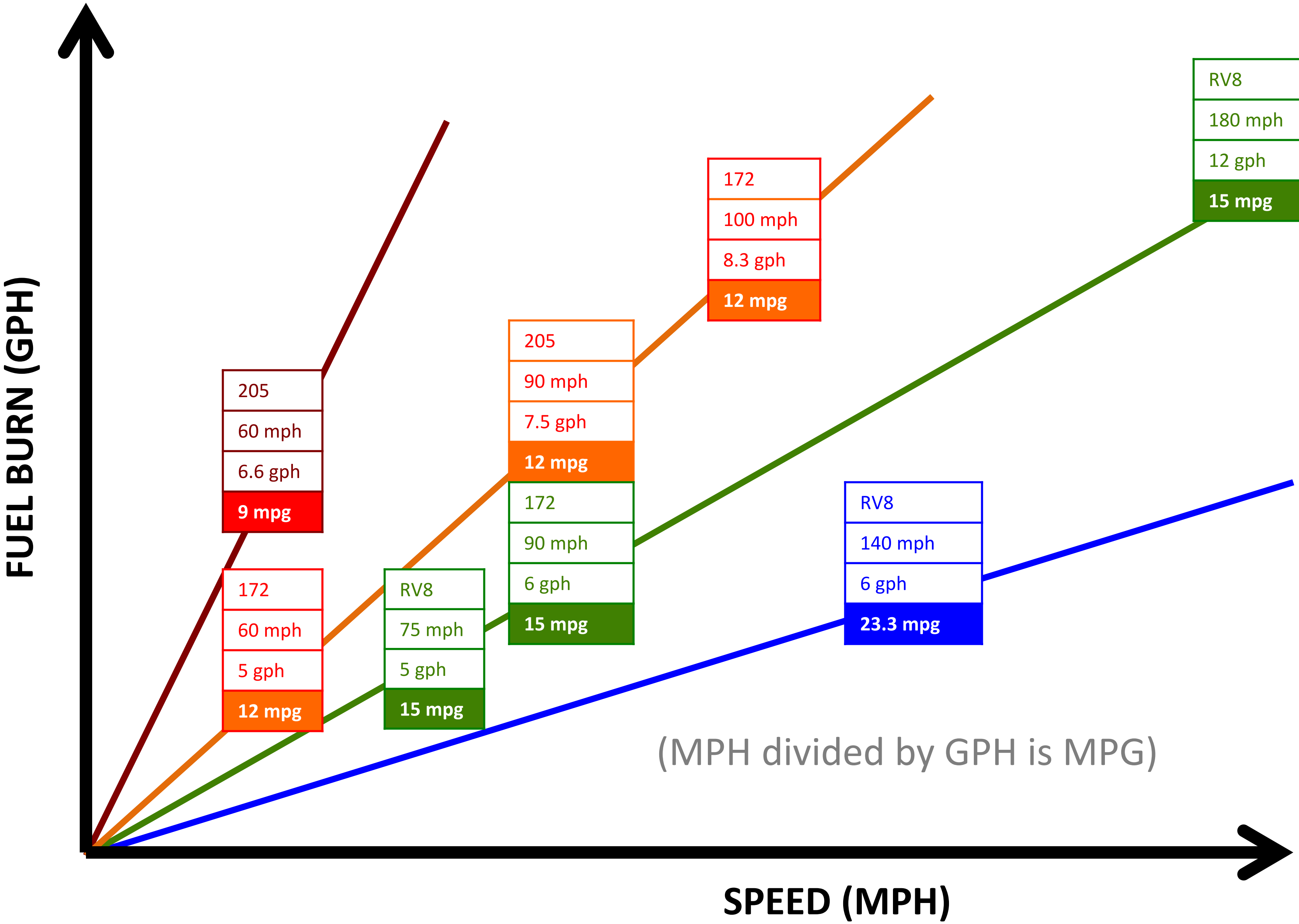
  SPEED (in miles per hour)

  divided by FUEL BURN (in gallons per hour)

  gives the FUEL EFFICIENCY (in miles per gallon).

- Let's do this on our graph. This is what we get.

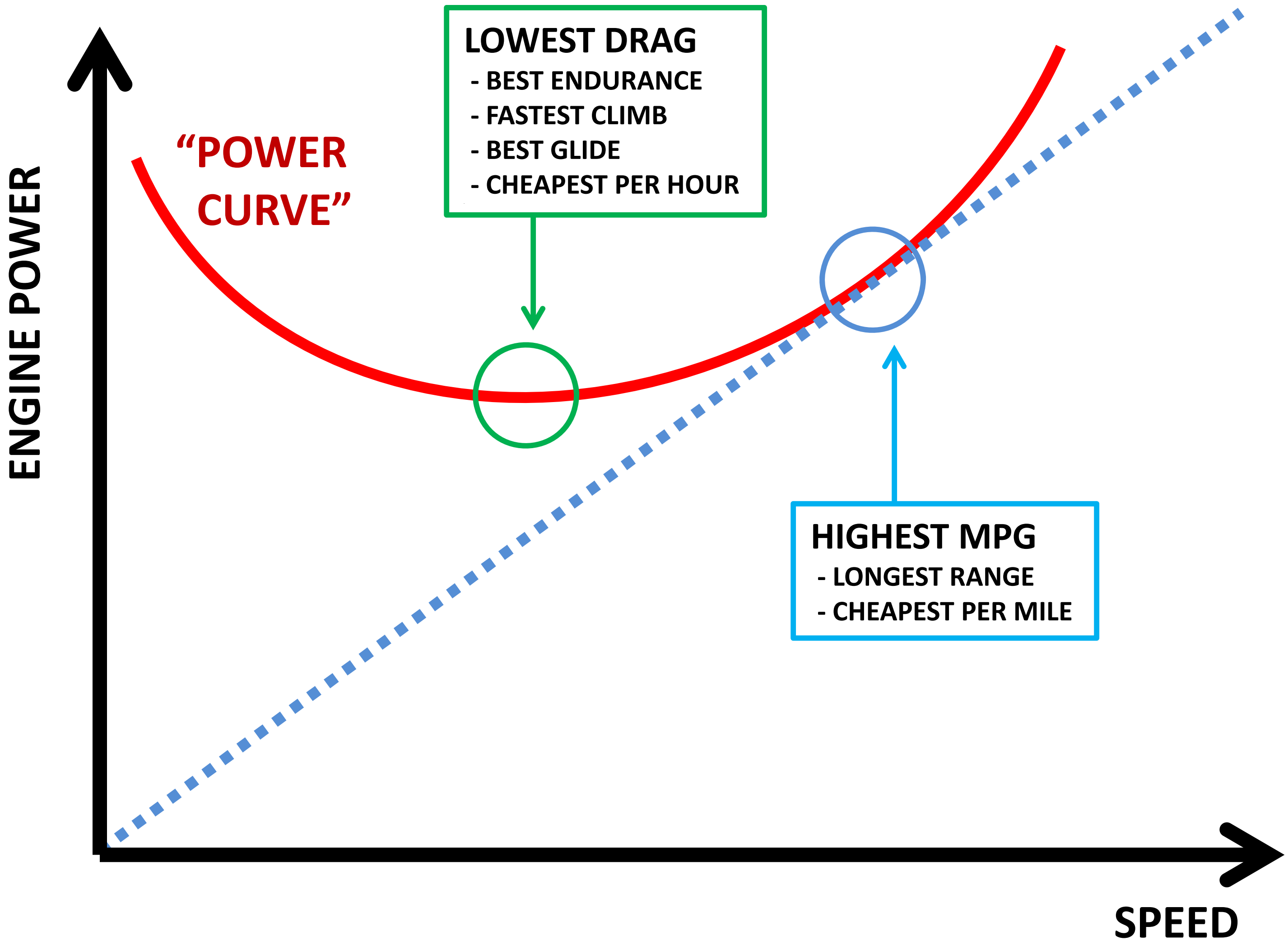
Boxes with same GPH line up. Low slope = high GPH!



Best speeds?

- Now, notice how the boxes seem to line up by MPG value.
- The boxes that are on the steep orange line (high ratio between fuel burn and speed) have lower MPG. Even worse for the red line.
- The boxes that are on the less-steep green line (lower ratio between fuel burn and speed) have higher MPG. Even better for the blue line.
- The simple fact that speed divided by fuel burn gives efficiency (i.e. miles per hour divided by gallons per hour gives miles per gallon) means that, regardless of what airplane we're talking about; Any combination of speed and fuel burn that is on a relatively steep line going through the origin will give relatively poor MPG, and any combination of speed and fuel burn that is on a less-steep line going through the origin will equate to a better MPG.
- So, if each airplane has a power curve… The highest-MPG point on that airplane's curve will be the point on the lowest-slope line going through the origin!

Best Speeds



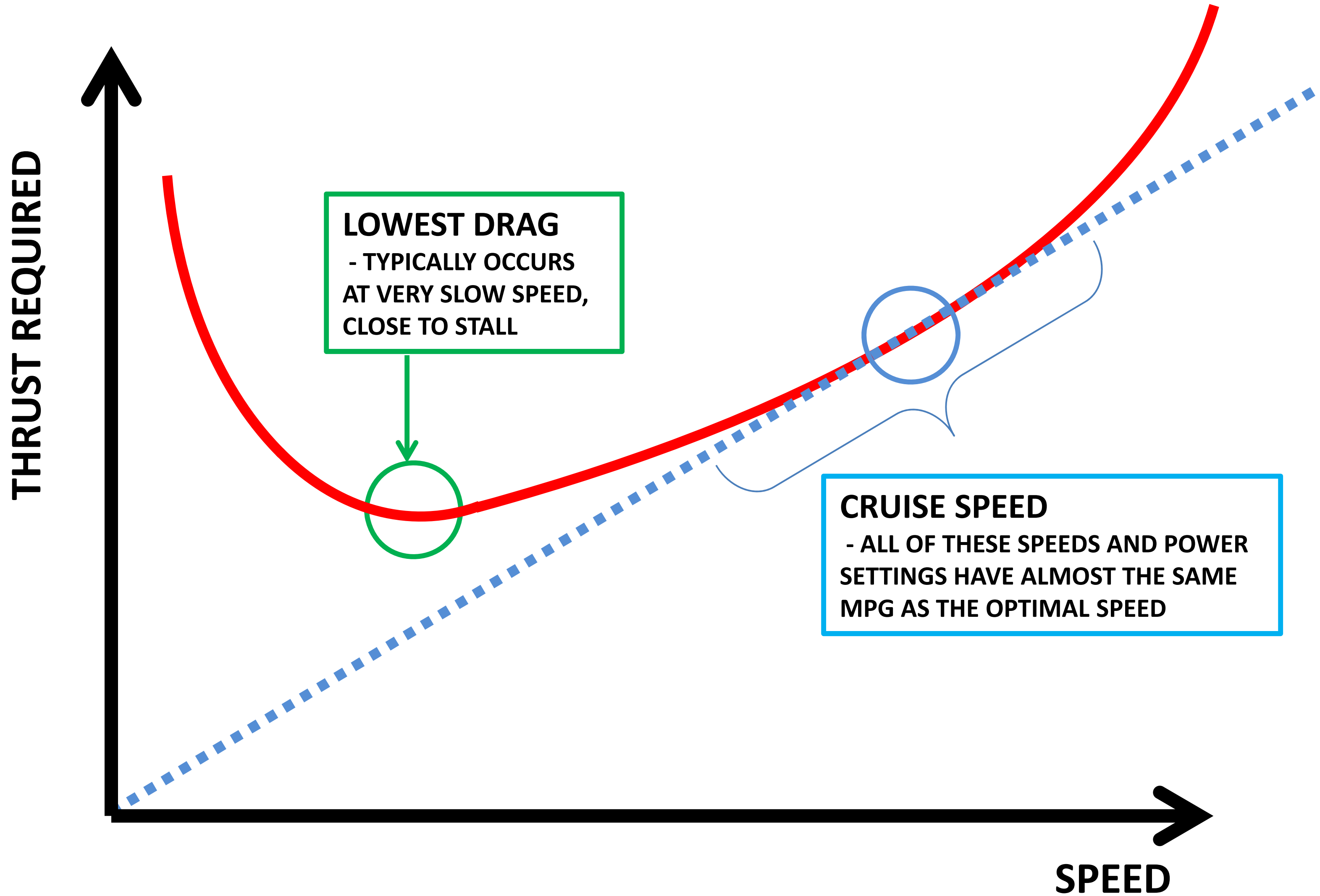
ENGINE POWER
"POWER CURVE"
LOWEST DRAG
- BEST ENDURANCE
- FASTEST CLIMB
- BEST GLIDE
- CHEAPEST PER HOUR
HIGHEST MPG
- LONGEST RANGE
- CHEAPEST PER MILE
SPEED

Best Speeds

- **The speed at the bottom of the power curve is the speed with the least total drag**.
  - So it requires the **least thrust**, the least engine power, the least fuel burn.
  - This means it's the ***longest-endurance*** speed. Handy for surveillance, sightseeing, building pilot hours, etc.
  - "Vx": It's also the speed where you have the **most *excess thrust* available**. That means it's the best speed for climbing (i.e. gaining altitude) steeply.
  - "Best glide": The highest L/D also means the **highest glide ratio**. So if you lose all engine power, this speed will allow you to glide the farthest, the least steeply.
- The power curve is horizontal at the bottom (gradient = 0), so you can go a little faster without burning almost any extra fuel: Better MPG. What speed gives the ***best* MPG**?
  - Remember the MPG graph:
    the speed that has the shallowest "straight line to the origin" has the most MPG.
  - So draw a **straight line from the origin that is tangent to the power curve**. That's the cruise speed (best MPG) for the airplane with that power curve.

I am "sweeping under the rug" two facts: (1) thrust is not the same thing as power. In fact, power = thrust x speed … and (2) most engines have non-linear relationships between fuel burn and power, or fuel burn and thrust. This means, for example, that the MPG lines you saw in slide 322 should actually be slightly curved. And there are two "lowest drag" speeds: one is Vx for minimum thrust (which makes for the steepest climb angle and the shallowest glide angle) and the other is Vy for minimum power (which makes for the fastest climb).

Best Speeds (More Realistic)

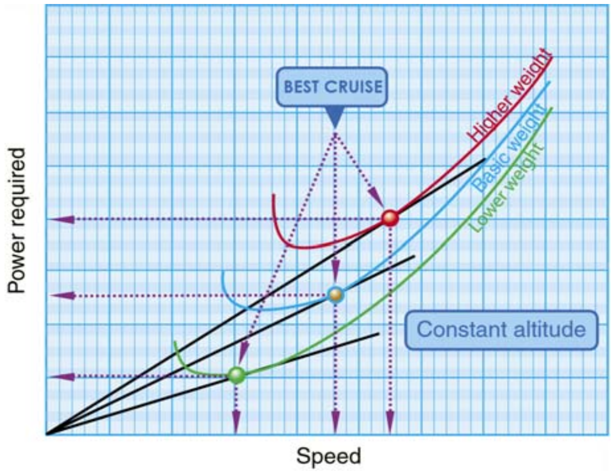


Best Speeds (More Realistic)

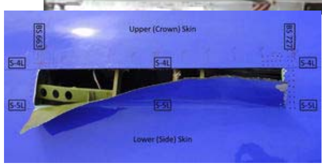
In most airplanes, the power curve is not symmetric, it's more like a "Nike swoosh", with a steep left/slow side and a shallower right/fast side that only gets steep again close to Mach 1. This is because, typically, induced drag only rises steeply at very slow speeds and high angles of attack. This means two things:

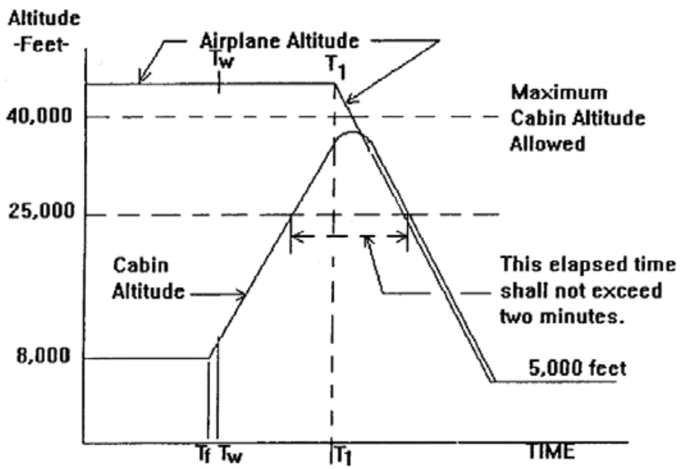
– The minimum-drag speed tends to be very slow, close to the stall speed. In practice, it is impractical to fly an airplane so slowly for very long, except gliders and extremely underpowered airplanes e.g. ultralights and electric airplanes.
– The best-MPG speed occurs in a region of the curve that tends to be relatively flat. That means that applying quite a bit more (or less) power, and going quite a bit faster (or slower), often results in almost the same MPG as the optimal speed. Most airplanes cruise at about 115%-120% of the best-MPG speed, and still get about 90%-95% of the optimal MPG.

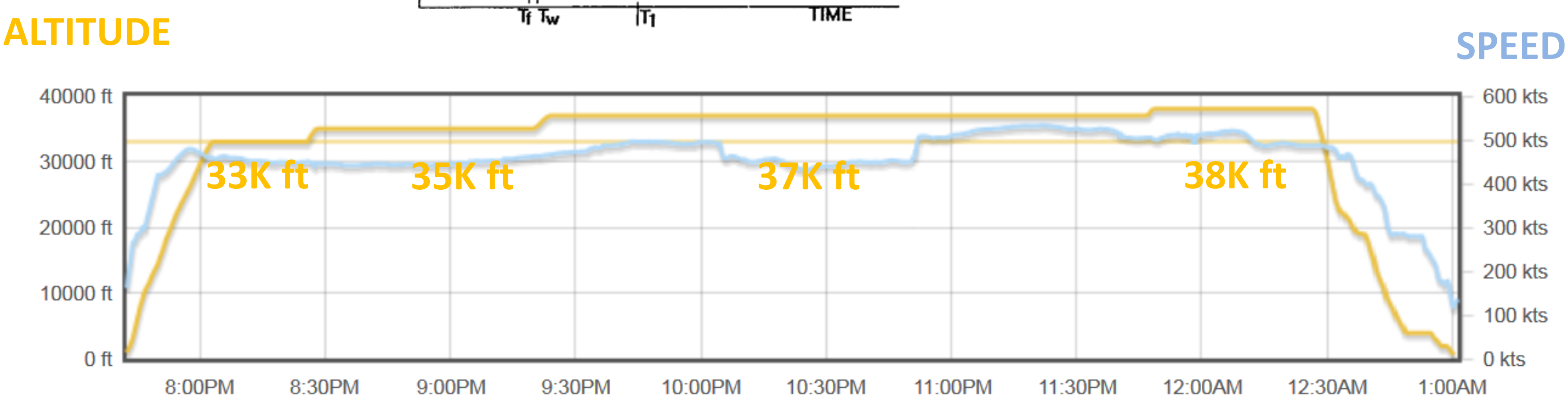
One final note: The heavier an airplane gets, the more induced drag there is, so the more thrust is required for any given speed… but at least the cruise speed gets a little faster. That's because the best cruise happens at a certain angle of attack, not at a certain speed! More weight means that more speed is needed at that angle of attack to generate enough lift.



Best Altitude







(LAX to JFK - Delta 757)

In general: **Fly as high as you can**! The higher the altitude, the less dense the air. Dynamic pressure is $\frac{1}{2}\rho V^2$, and aerodynamic forces are usually a multiple of dynamic pressure. So if you fly higher (at a lower ρ)…

- … either going at a given speed generates less drag, or…
- … you can go faster and generate the same dynamics pressure and therefore the same lift and drag.

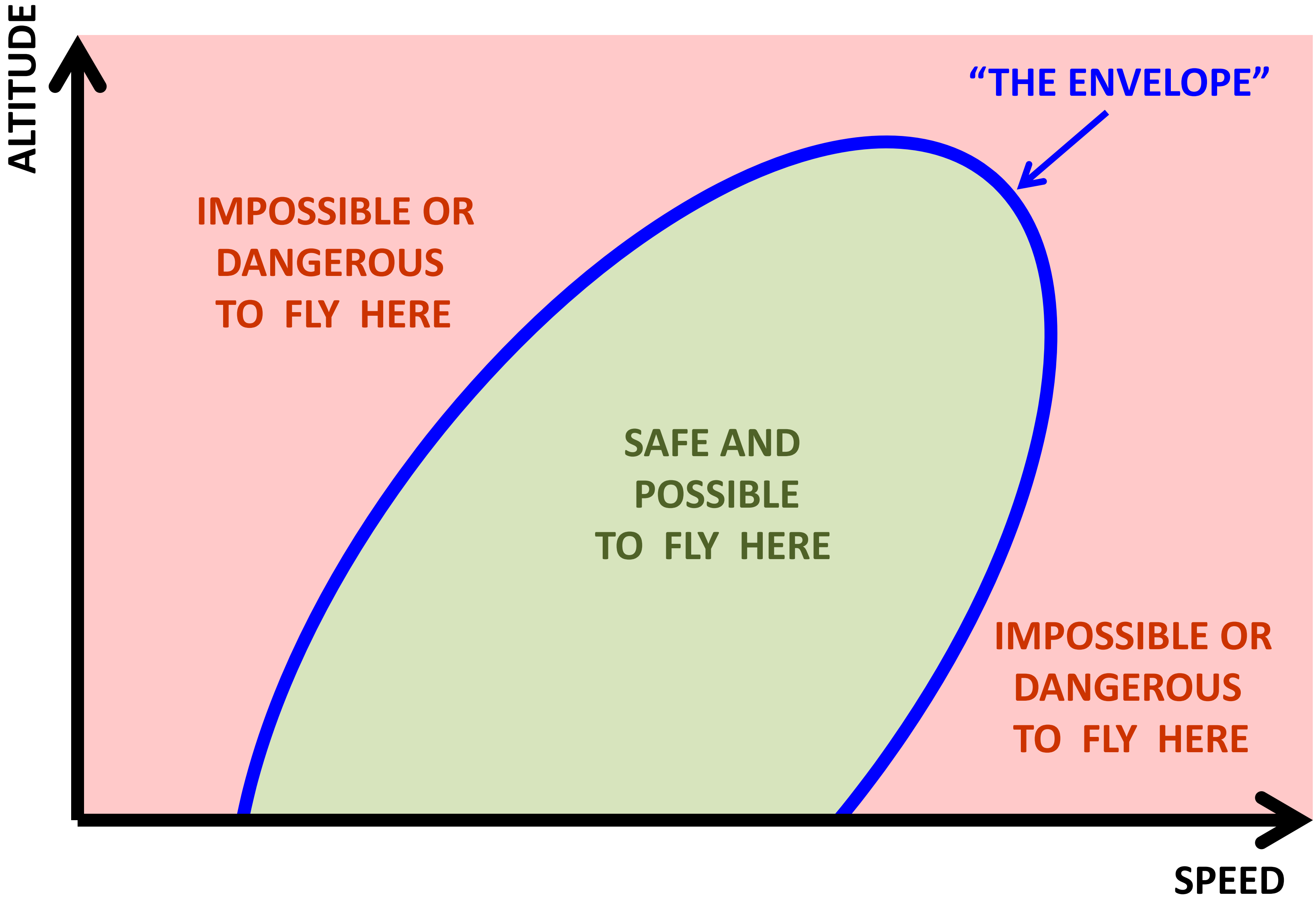
However, there are three complicating factors.

– Air at 40,000 feet is thin enough to cause brain damage after only a couple minutes of exposure. Even in an emergency loss of cabin pressure, airlines are not allowed to expose passengers to air this thin. So they generally do not fly higher than ~41,000 feet. FAA regulations also say that the cabin pressure, typically equivalent to an altitude of 8,000 feet, may not exceed the equivalent of 25,000 feet for more than 2 minutes: If the pressure drops quickly, the airplane has 120 seconds to descend to 25,000 feet (and recall that the airplane has a maximum dive speed, typically related to the flutter speed), also taking into account the crew's reaction time. Any loss of cabin pressure causes the pilots to quickly descend to at most 15,000 feet, where the air is safe to breathe, and ideally on to 5,000 feet.

– The lower the air pressure, the lower the temperature at which water boils. At 50,000 feet, the pressure is so low that water boils at room temperature. This means your blood, your saliva, your tears… would boil at 50,000 feet. This is called the Armstrong Line. Airplanes only fly higher than 50,000 feet if occupants are wearing pressurized suits (i.e. "astronaut suits") even if the airplane is pressurized.

– Recall that, the higher the CL of a wing (i.e. the higher its angle of attack), the lower its Mcrit (i.e. the speed at which it begins to make shockwaves, the increase in drag at the start of the "sound barrier"). As an airplane flies higher into less-dense air, it needs to either fly faster or fly at a higher angle of attack, i.e. at some altitude it will start to make shockwaves. So **most jets cruise at the altitude that is as high as they can fly without making shockwaves**. As they burn fuel and become lighter, the wing does not need to generate as much lift, so they can then fly up into thinner air without having to increase speed or angle of attack, i.e. without making shockwaves. So **during long flights, jets typically cruise higher and higher as they burn fuel**, because they are able to fly in less and less dense air without needing speeds or angles of attack that would trigger the formation of shockwaves.

“The Envelope”

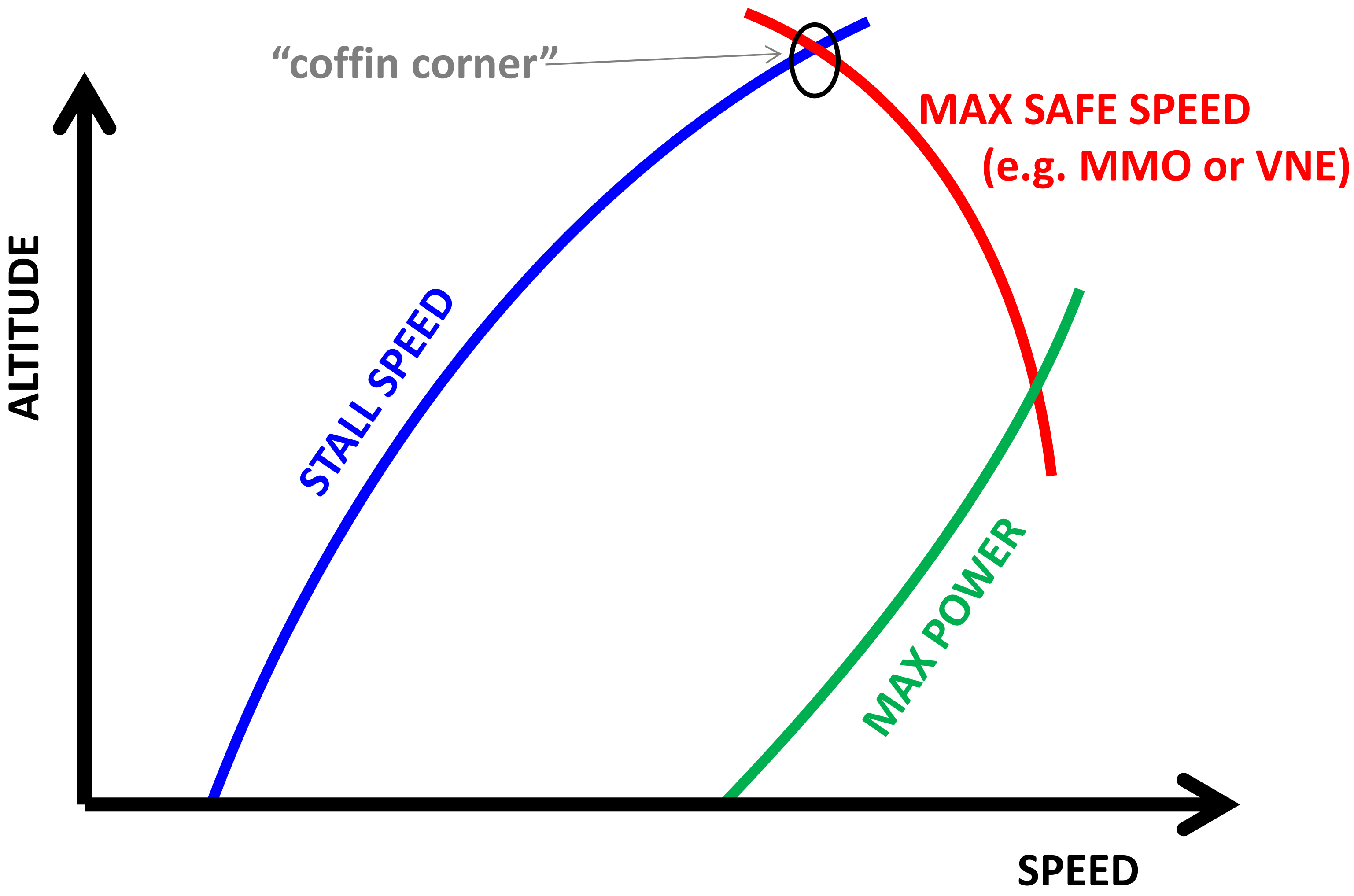


"The Envelope"

- So far we have been talking about optimal performance. But given an airplane, what are the extremes of its performance?
- Most people know that "pushing the envelope" and "the edge of the envelope" originate from flight-testing, from exploring these extremes.
- Mathematically, the "envelope" is just the boundary between one region and another, typically between the region where something is possible and the region where it is not possible.

  (If you're standing in the middle of a flat field, what are all the points on the ground that you could hit by throwing a ball? The circle-shaped line at the edge of this region is its "envelope").
- For airplanes, the "flight envelope" is one of various graphs that separates safe (or possible) combinations of flight parameters (typically: speed and altitude) from unsafe (or impossible) combinations.
- The altitude/speed flight envelope typically looks like this. Why?

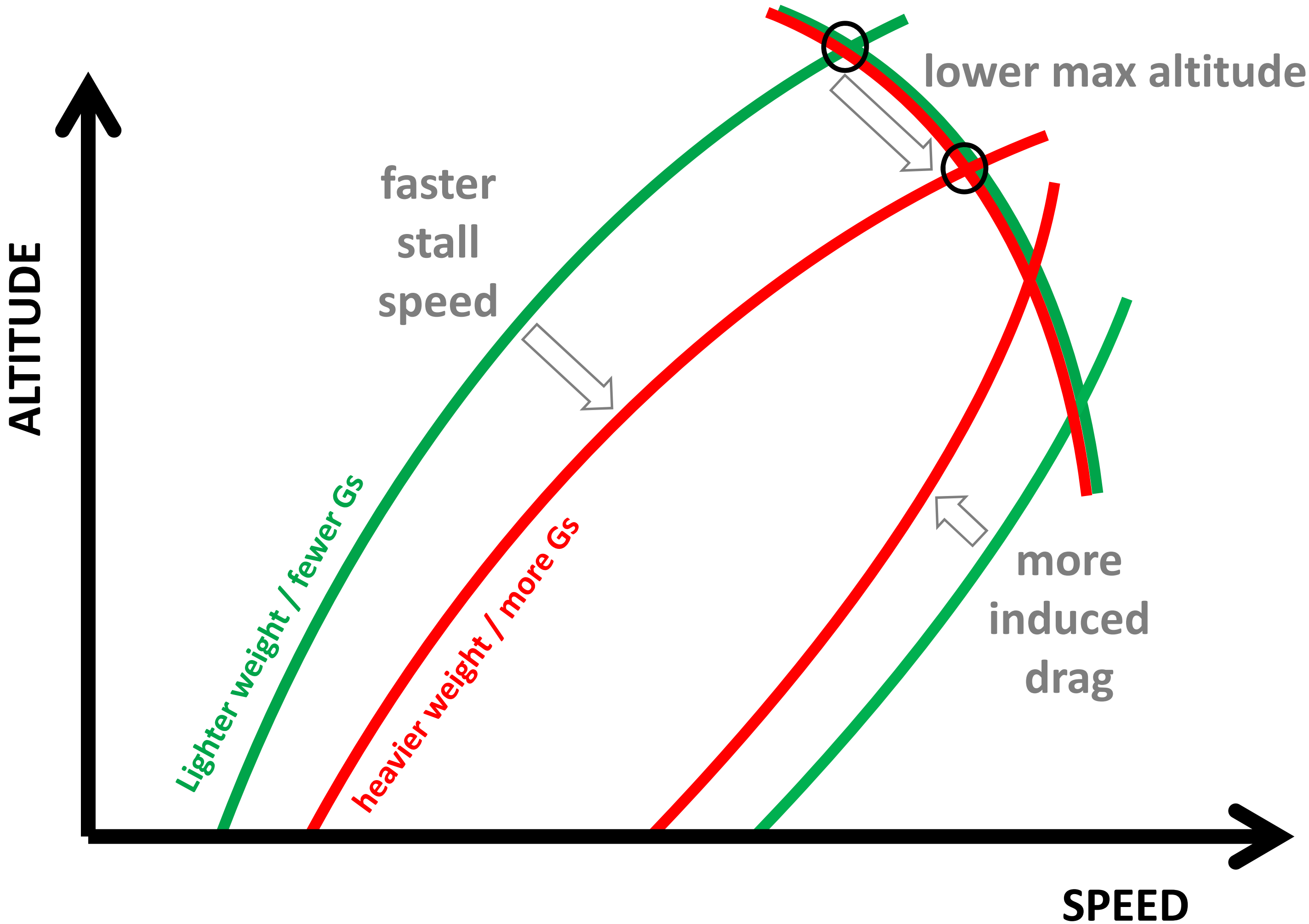
"The Envelope"



“The Envelope”

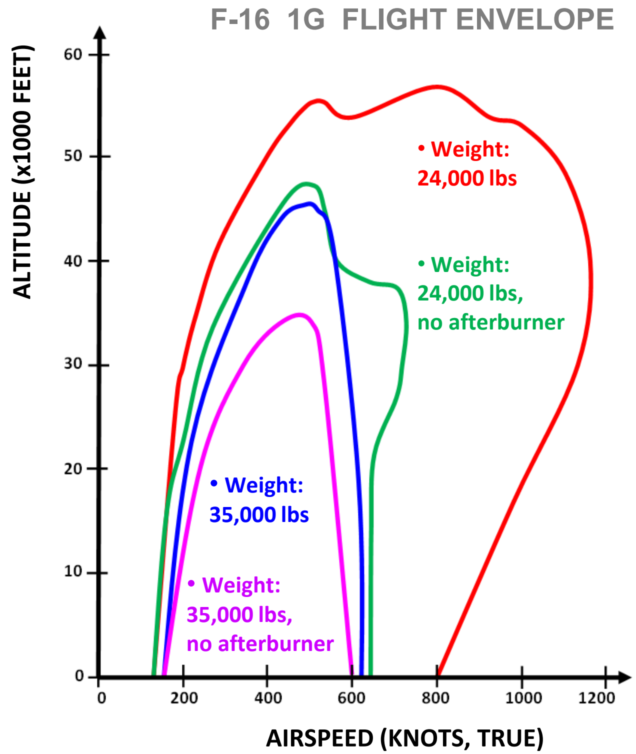
- Assume a “standard day” (sea level at 15°C and 29.92Hg, air gets colder & less dense with altitude… look up the “standard atmosphere”) and a given airplane with a given configuration (e.g. flaps up, gear up) and a given weight (e.g. max weight).
- There is some speed at which the airplane stalls. Specifically, there is some dynamic pressure ($\frac{1}{2} \rho V^2$) at which the airplane hits its “stall” angle of attack. So as density goes down (e.g. **as altitude goes up), that stall speed goes up.**
- Max engine power gives a max speed… or, rather, a max thrust, which fights a max drag, at a max dynamic pressure: **As you go higher, you can fly faster due to lower** ρ.
- At increasing Mach numbers, various effects kick in: a shockwave over the wing, buffeting, Mach tuck, high temperatures, high localized pressures. A jet airplane can only take so much, and has a **max safe Mach number**, “MMO”. The speed of sound goes down with altitude, so the max safe speed starts going down past altitudes where the airplane is capable of reaching MMO.
- At the “**coffin corner**”, the airplane is both at MMO and on the verge of stalling! (U-2s cruise there: At ~70K feet, stall buffet at ~425mph, Mach buffet at ~435mph).
- Slow airplanes often do not have an unsafe Mach number or the ability to reach VNE in level flight: You can jam the throttles forward at any altitude. Piston engines do produce less thrust at altitude. (Jet engines run very lean and don’t need as much oxygen; Piston engines could use all the oxygen they can get). So a slow airplane can set the engine at max thrust, and climb until it’s at the verge of a stall: It will be **going as fast as physically possible AND as slow as physically possible, at the same time!**
- Other factors may “chop off” parts of this graph. Some system, component, or device might not like certain combinations of speed and altitude.

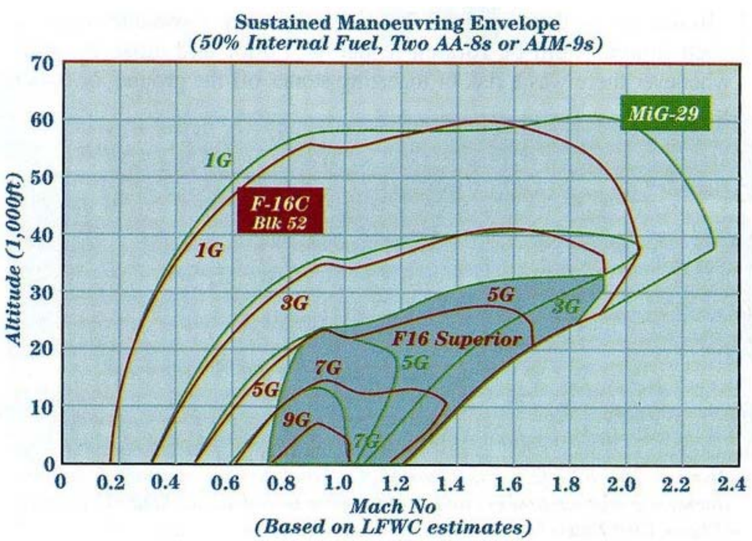
Impact of Weight and/or “G”s



Impact of Weight and/or "G"s

- Notice that "the envelope" for a certain airplane is really the 1G envelope for that airplane at a certain weight.
- If the airplane is heavier, it will have worse induced drag, so the max speed will be lower. And the wings must generate more lift, i.e. they need more dynamic pressure at the critical angle of attack at the verge of the stall, so the stall speed (at any given altitude) gets faster for the heavier airplane. Therefore, the max altitude becomes lower.
- So although lower weight is important for the ability to carry more payload and have greater fuel efficiency, it is also important for absolute performance (max speed and altitude).
- To the right are four envelopes for a model of the F-16. Two different weights, and two different power settings. (Not using afterburners does not change the stall speed but does restrict the max speed and altitude, almost like being heavier).

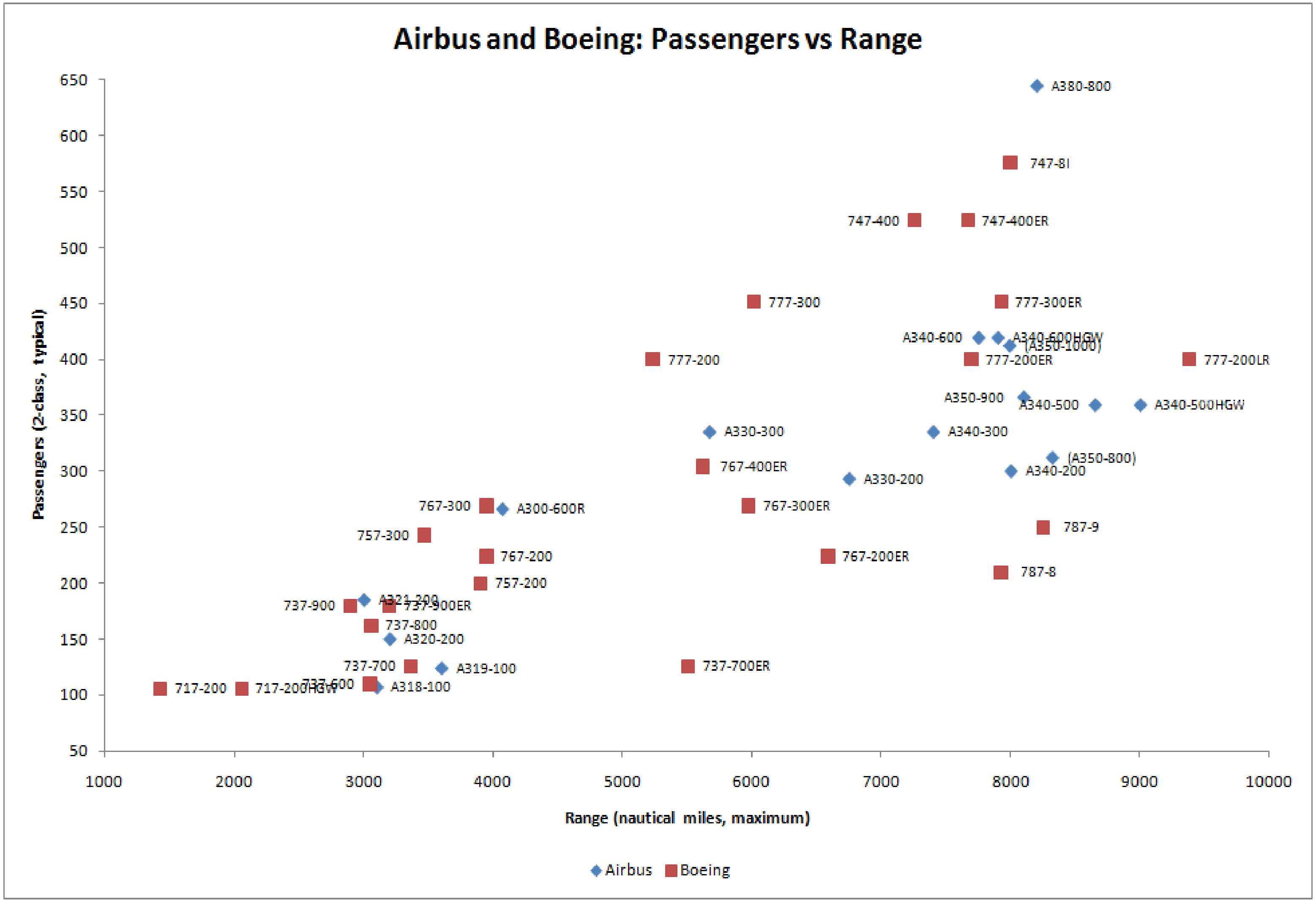




Pulling Gs (i.e. making tight turns) also requires the wings to make more lift. So, for the exact same reasons, the "2G envelope" and "3G envelope" (and so on…) of an airplane are smaller and smaller than the 1G envelope.

These multi-G envelopes come in handy for comparing fighters. For what combinations of speed and altitude can an F-16 pull more Gs than a MiG-29? If you're an F-16 pilot, this could be a life-or-death question!

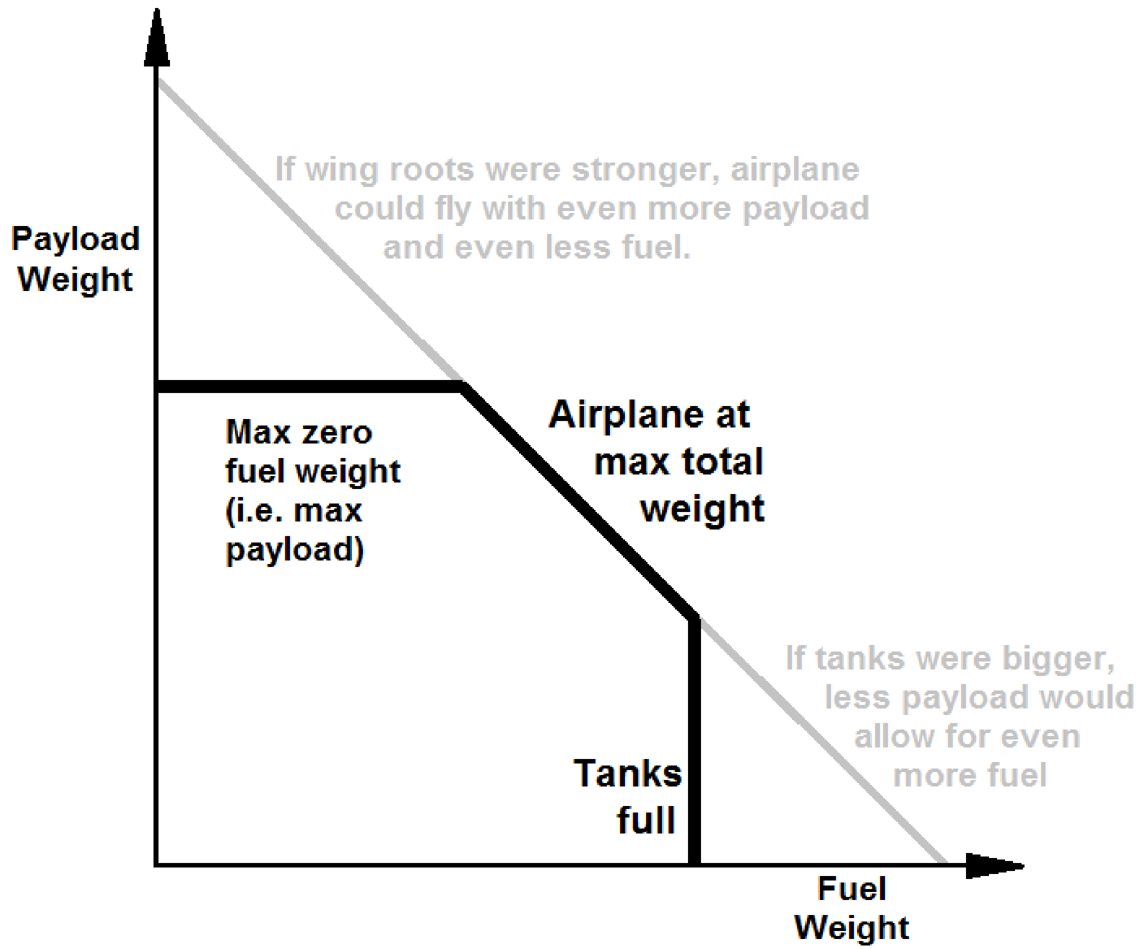
Payload and Range



Payload and Range

- The questions “How much stuff/people can this airplane carry?” and “How far can it go?” (arguably followed by “How does the max takeoff weight go down if the runway is not super long?”) are the most important when describing a transport airplane (and a bomber, for that matter).
- Thinking about these curves is the first step in designing a new airliner. Look at all the commercial flights out there: How many people do the airlines carry in each flight, and how far does each flight go? Are flights in certain-sized airplanes over certain distances always full (if so: Make a slightly bigger derivative airplane!) or never full (in which case: Make a slightly smaller derivative airplane!), are some flights often flown with full fuel and barely able to reach their destinations if there’s a headwind (if so: Add some fuel tanks!), etc.
- In short: If the airlines could change the fuel capacity and/or payload capacity of some of their airplanes, how would they change them? The answer is typically expressed in terms of payload and range… and the answer drives what airplane should be developed next.
- (Another aspect of this question, also key to “What airplane should be developed next?”: What do the payload-range curves look like for airplanes due to be retired in 5 to 10 years? If we develop a new airplane to replace them, would it sell? Also, what markets are currently growing, what regions of the world are seeing more travelers and cargo, what are the distances of the flights in those markets, and how much stuff/people will they want to be flying over those distances in a few years?)
- Different airlines will have different answers to “How would you change the payload and/or fuel capacity of some of your airplanes” and to “What would the ideal payload-range curve be of the airplanes you think you’ll want to buy in a few years?”. Island-hoppers in Hawaii or Japan might want lots of payload and relatively little fuel (i.e. above and to the left of most of the points on the chart, requiring higher zero-fuel weights). Airlines doing more point-to-point flights rather than hub-and-spoke, e.g. flying narrowbodies across the Atlantic, will want smaller planes with more range (i.e. below and to the right of most of the points). Manufacturers do their best to please everyone, but they do pay more attention to the airlines that will buy more airplanes (e.g. American, Delta, Southwest, United, etc. generally get exactly what they want).
- When Boeing and Airbus decide what their next derivative should look like (How long should the A330NEO fuselage be? Should the 777-8X have fuel tanks in the belly or just wing tanks?), this is what they think about. What do the airlines want? How many of ***this*** derivative would we sell, how many of ***that*** derivative would we sell?
- Boeing has a public webpage (!!!) for its “Current Market Outlook”, including a PDF that details the latest forecasts on which kinds of transport airplanes will sell where in the world, for what kind of role, over the next 20 years. It’s fascinating reading, and offers hints about what the next Boeing might be like: http://www.boeing.com/commercial/market/long-term-market/downloads/

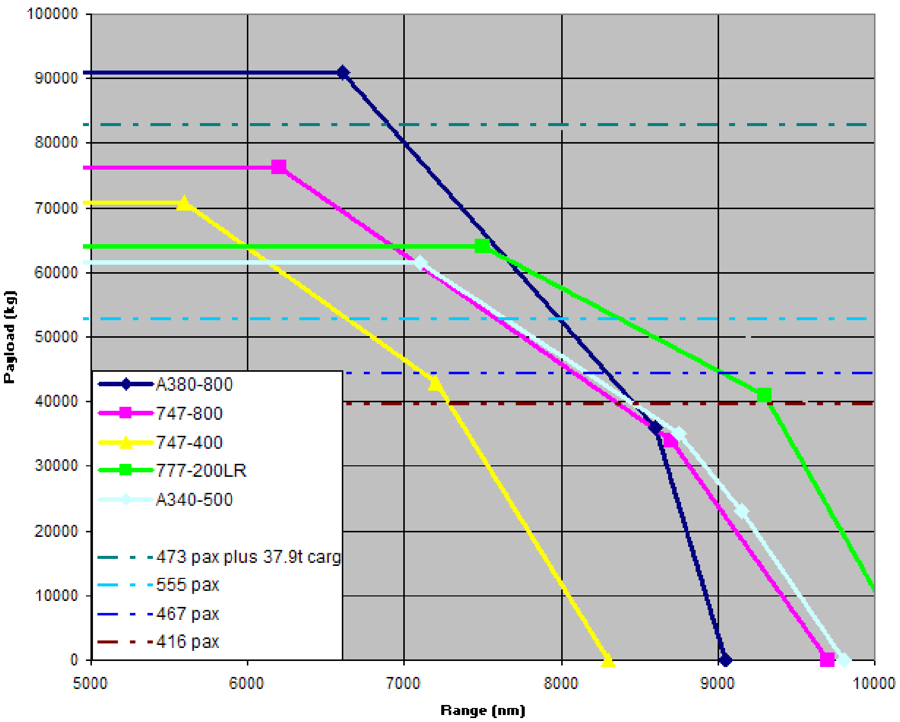
Payload & Fuel Weights

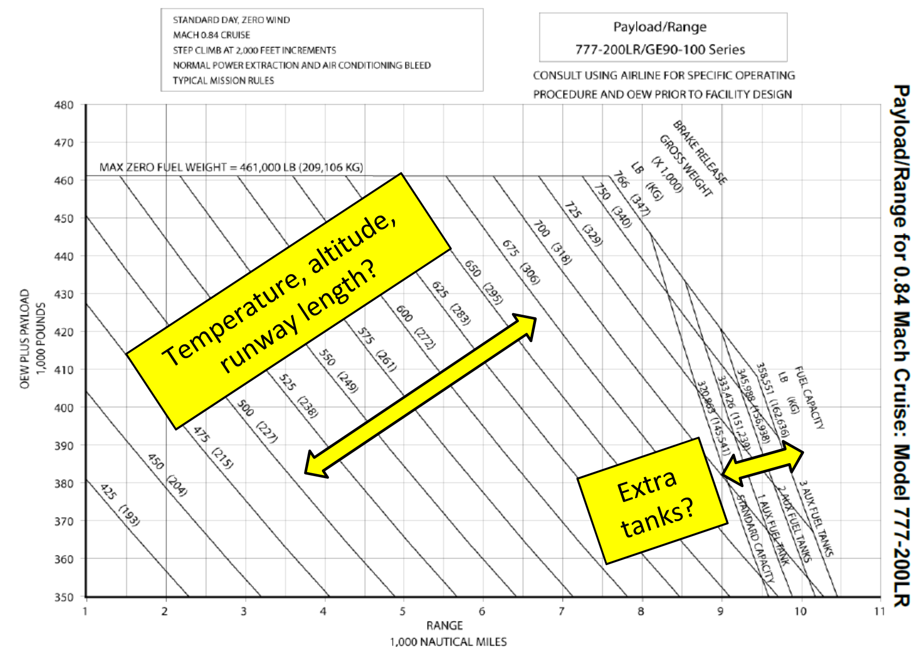


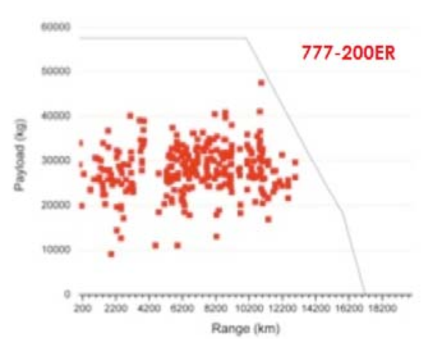
Payload & Fuel Weights

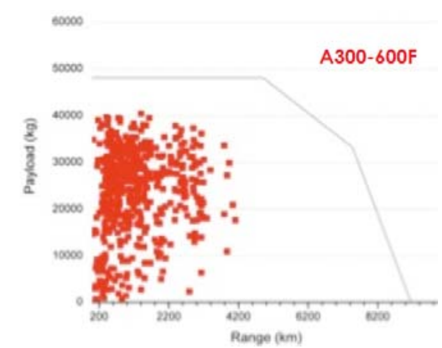
- Let's say that **total airplane weight = airplane empty weight + payload weight + fuel weight**
- An airplane will have a certain max total weight.
- An airplane can fly with full fuel tanks, or with a nearly (for some airplanes: totally) full cargo bay and passenger cabin… but not both. This means the max weight can be reached by any[*] combination of fuel and payload.
- [*] Not "any" combination: (1) The fuel tanks can only hold so much fuel, and also…
(2) There's a min weight for the fuel, because too much weight in the fuselage and too little weight in the wings could cause excessively high bending moments at the wing root
(i.e. Structurally, there's a "max zero-fuel weight" for the airplane).
- This means that each airplane can carry any combination of payload and fuel that is bound by this three-line region. If it fills the tank, it can fly its max range but with limited payload. If it carries max payload, it won't be able to fill the tanks and will only have a limited range. Etc.
- Most airliners can just about fly with full tanks and max passengers ***if*** they don't also carry cargo (e.g. mail). If they also want to carry cargo, they will have to fly with less-than-full tanks.

Payload-Range Curves and Derivatives









Payload-Range Curves, and Derivatives

- With full tanks, the less payload you have, the lighter the airplane is, and the longer the range gets (because of less induced drag). So the right-most segment ("full tanks") of a Payload-Range curve (as opposed to the Payload-Fuel curve on slide 338) is not vertical: It is slightly diagonal, down and to the right.
- The best way to compare the overall capability of different transport airplanes (airliners and cargo freighters) is to compare their payload-range curves. Again, a transport airplane is defined by how much it can carry, and how far.
- For example, look at those widebodies. It should be no surprise that the A380 can carry more payload than any other airliner, and that the 777-200LR has the longest range. But it turns out you can only fly a full A380 if your range is relatively short. To carry enough fuel to fly more than about 6600 miles, you can't carry the maximum number of people that would physically fit in an A380. Surprisingly, if you're flying farther than about 7600 miles, a 777 can carry more people than an A380! Similarly for the 747, which is bigger, versus the A340, which can fly very far and still carry pretty close to its max capacity.
- As we will discuss in the next slide, a set of closely-related derivatives (e.g. some variants of the 777) will have slightly different payload-range curves. Some can carry more fuel (e.g. have auxiliary tanks in the belly), some can carry more payload (i.e. have longer fuselages and stronger wings). If the max weight is the same, then at the same payload, the longer one will have less range… and to make the same range, the longer one must carry less payload. This is due to the higher structural weight of the longer one.
- Even a single airplane (e.g. 777-200LR) will have different payload-range curves depending on its max weight. On a hotter day and/or while taking off from a shorter runway, the 777 has to take off with a lower max weight, so it must sacrifice some fuel (range) and/or some payload. And the addition of auxiliary tanks in the belly would allow for even longer ranges if operators are willing to sacrifice payload (i.e. not carry as many people).
- Data is gathered about the payload and fuel load of commercial flights. So given an airplane type (e.g. the A300 Freighter, and/or the 777-200ER), this data could be displayed as red dots plotted on the payload-range curve. The payload-range curve is an envelope of maximum allowed combinations, so typical flights are not right up against these limits. Do most flights come close to carrying the max payload? Or to requiring the airplane to fly its maximum range? That data – the red dots – inform the airplane manufacturer about how airlines are actually flying the airplanes, about how the airplane could be modified in order to help it sell better. (For example: Look at these red dots. Airlines seem to never carry as many people as possible in their 777-200ERs, but some do fly these airplanes very close to their max range. So Boeing should make a longer-range version! This is where the 777-200LR came from). That brings us to…

Derivatives and "Family Planning"

Heavier:
+ engine thrust
+ landing weight
+ wing root bending
+ fuselage bending
+ maneuver loads
+ wing area?
+ high lift devices?

Longer:

+ fuselage bending

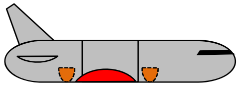
+ elevator loads

- rudder loads ☺

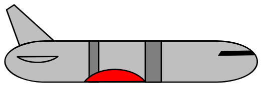
+ gear height?

+ landing weight?

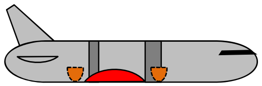
+ wing root bending?
(if less fuel in wings)



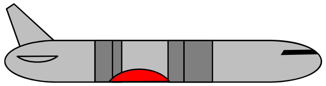
shortened
(less fuselage, more fuel)



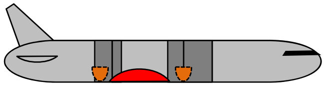
original



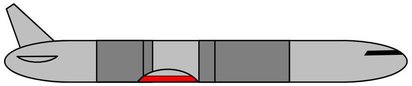
extended range
(more fuel)



stretch
(more fuselage)



heavy stretch
(more fuselage, more fuel)



super stretch
(even more fuselage, less fuel if max payload)

Say that operators want an airplane like yours, but with more range, or with the capability to carry more payload (or so you deduce, from the model's usage data statistics). So you decide you want to design and sell a derivative.

- **Increasing the max weight.**
  Typically, a version of an airplane with a bigger fuselage and/or carrying more fuel will be heavier! This will require serious engineering (i.e. inve$tment) to develop: Bigger engines, stronger landing gear and control surfaces and wing and fuselage structure (to deal with the higher loads from the higher weight). Maybe even larger wings and high-lift devices. If this is what the market wants, it often pays to do it. Examples: 777-300 and 200ER, MD-80, 737-900, A321, 747-8, 787-9, Cessna 207.
- **Could your derivative carry more payload without needing a higher overall max weight?**
  If your customers often fill up the airplane but rarely fly it very far… Could they put more weight in the fuselage (payload) and less weight in the wings (fuel)? Only to a limit, because this would cause more wing-bending. A derivative that addresses this demand would have to beef up the wings (or implement Maneuver Load Alleviation) so they can take the higher bending. The fuselage is then typically "stretched" i.e. lengthened (more seats and/or cargo volume) and correspondingly strengthened (there'll be higher fuselage bending loads in the middle of the longer tube). The elevators and horizontal stab's need to be strengthened too, to provide greater maneuvering forces (due to the higher moment of inertia, and the longer size means the tips of the fuselage need to move faster through the air). Taller landing gear is ideal but typically impractical, so typically we add a tail skid. These changes increase the structural weight (beyond just the weight of the added "hoops" of fuselage), so if the max weight stays the same, your useful load (payload + fuel) decreases. Examples: DC-8-61, E-195, 787-10.
- **Could your derivative fly further without needing a higher overall max weight?**
  If your customers rarely fill up the airplane, but fly it to the limit of its range… just add auxiliary tanks to the belly. Simple! Cheap! But filling those tanks would mean the fuselage can't be filled… unless the fuselage is shortened. Shortening the fuse requires a larger rudder, to make up for the shorter moment arm, in case of an engine-out. But a shorter fuse allows for more lightweight structure, so even more weight (not just the weight of the removed fuselage "hoop") is "freed up" for even more fuel. That structural weight reduction would be less simple (more expensive) than just adding aux belly tanks, but would make for a more capable airplane, if the market is willing to pay for it. Examples: 720, 737-500, 747SP, ERJ-135LR, A330-200.

Note: If you value affordability over fuel-efficiency, and foresee a "family" for your new airplane, you could over-design the original model so that fewer modifications are needed for the derivatives: Start off with extra-strong fuselage and wings and horizontal stab in case you want to make a stretch later, an extra large rudder in case you might want to make a shortened version, etc. If you do, the derivatives will require less re-engineering so they'll cost less to develop… However, each derivative ends up less optimized, i.e. less fuel-efficient. (Airbus generally does this more than Boeing, making Airbus airplanes cheaper but less fuel-efficient). The extent to which you do this depends on oil prices. If fuel seems to always get more and more expensive – or is simply too volatile – then it makes sense to make the most fuel-efficient airplane possible (e.g. 787). But if oil prices are expected to remain steady or go down, then it may be cheaper overall to have an airplane that burns a little more fuel but that was much cheaper to purchase (i.e. that was less expensive to develop and manufacture, i.e. not as perfectly optimized… or not as high-tech in general).

Remember: The goal is always to minimize the overall lifetime cost of the airplane, i.e. the total cost of acquisition, fuel, maintenance, etc., over ~25 years. Say that an airline wants an airplane that can carry 170 people 3000 miles. What will be the total cost of doing so for ~25 years in a 737? How about in an A320? The airline will choose the airplane that will cost less in total over those years. (This depends on the airline. For example, if an airline has a bunch of 737s but no A320s, then buying A320s would bring the added cost of buying and storing more spare parts, training pilots and mechanics, etc., while simply buying more 737s would not have those added costs. Airlines sometimes do "switch", though!)

For even more information…

- I have recently reduced the amount of information in my "Understanding Airplanes" course.
- The original version included "special topics" that do not apply to most mainstream airplanes but that are very interesting: Aerobatics, stealth airplane design, vertical takeoff and landing technologies, aviation safety statistics and trends, record-breaking airplanes, and the latest developments in the world of aerospace technology such as reusable spacecraft, UAVs, automation, more fuel-efficient approaches to landing, parachutes that can save an entire airplane, 3D printing, etc.
- The full slide decks for these "special topics" are available at UnderstandingAirplanes.com in the **"Resources" page**. As with the slides for the class itself: Feel free to download them, print them, share them, etc. I hope to soon be adding videos of these "special topics" presentation to the website.
- UnderstandingAirplanes.com 's **"Resources" page** also contains tons of links to informative videos, online courses, books, talks, and other resources about airplanes, aeronautical engineering, aviation history, and flying. Check it out!
- Any feedback would be sincerely appreciated: UnderstandingAirplanes@Gmail.com

Thank you! ☺

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4	compact tension specimen	UFRJ, Federal University of Rio de Janeiro	Reproduced with permission	https://www.youtube.com/watch?v=N2wtVLYXzDI
4	767X "Hunchback of Mukilteo"	Boeing	Previously approved for public release	http://designblog.nzeldes.com/2008/05/aesthetics-and-design-boeings-lar-rule-saves-the-day/
6	diagram: airplane key components	NASA	Public Domain: government	https://www.grc.nasa.gov/www/k-12/airplane/airplane.html
7	Wright Flyer	Library of Congress	Public Domain: >70 yrs	https://www.theatlantic.com/photo/2014/08/first-flight-with-the-wright-brothers/100796/
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TWO SLIDES PER PAGE

About **Bernardo Malfitano**:

Bernardo currently works in the Airplane Configuration group within the Product Development organization of Boeing Commercial Airplanes. He performs analyses, studies, and sometimes tests, around proposed features and configurations for future airplanes. This determines the optimal shapes, materials, locations, and manufacturing processes for new airplane parts, so as to minimize drag, weight, cost, and risk.

For the previous 10+ years, Bernardo worked as a structures engineer / researcher, specializing in fatigue testing, analysis models, and maintenance planning. Bernardo was one of Boeing's experts on "airplane aging" issues, and taught new Boeing engineers how to do fatigue analysis and to plan airplane maintenance.

Bernardo earned his BS from Stanford University and his MS from Columbia University, both in Mechanical Engineering. Most of his academic career leaned towards aerodynamics and propulsion: i.e. many hours designing and running experiments in the wind tunnel and in the engines lab. He has also helped to design, implement, and test control/autopilot systems in UAVs and spacecraft.

In his spare time, Bernardo enjoys flying single-engine airplanes, especially his aerobatic RV-6. During summer weekends, he works as a journalist, covering airshows for aviation magazines and websites. He has flown himself to airshows as far away as Oshkosh. He has also built and flown models ranging from gliders and quadcopters to rockets and flying wings.