Introduction to Aerodynamics

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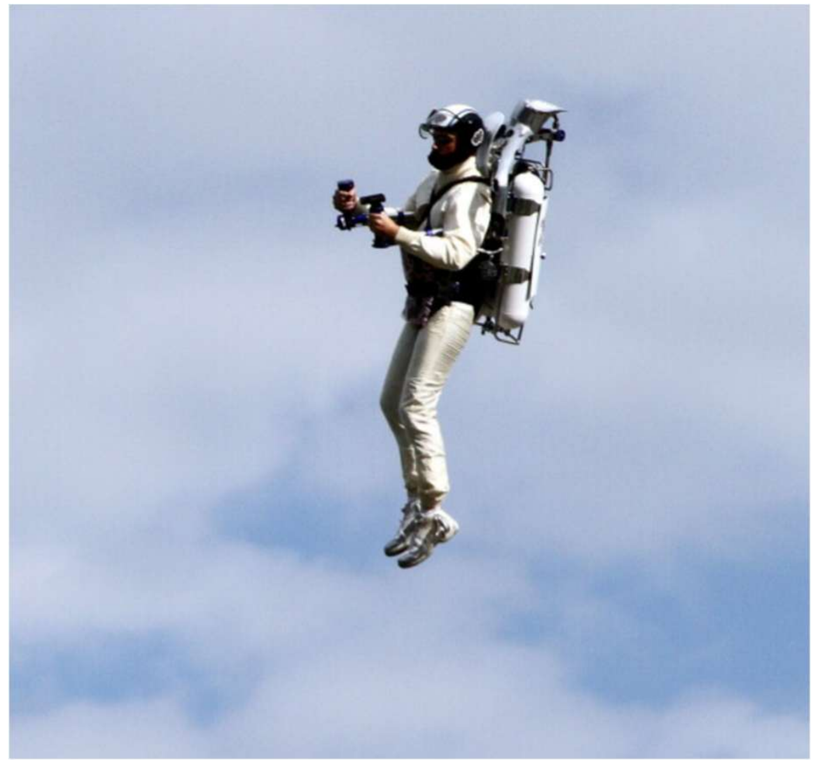
Objectives

- Familiarization with aerodynamic forces
- Associate aerodynamic phenomenon with forces on the airplane
- Apply knowledge of center of gravity and aerodynamics to estimate changes in aircraft performance and stability
- Understand forces during flight maneuvers, stalls, and spins

Outline

- Fundamentals of aerodynamics
- Forces of flight
- Stability
- Manuevering flight
- Aircraft Performance
- Stalls and Spins

Fundamentally: how do aircraft fly?



Newton's third law: for every action there is an equal and opposite reaction. Air is pushed down.

Not on Exam

Newton’s Third Law

No Wheels?

Wheels?

- **If the woman jumps forward, in which case does she go farther?**
- **Where does the energy go when she doesn’t get very far?**

Not on Exam

Concept of the wing

Move a lot of air a small amount, energy goes into lifting the plane, not fast-moving air

Not on Exam

Types of Energy

Potential Energy:
Mass x Gravity x Height

Kinetic Energy:
½ Mass x Velocity^2

Work (Thermal Energy):
Pressure x Volume

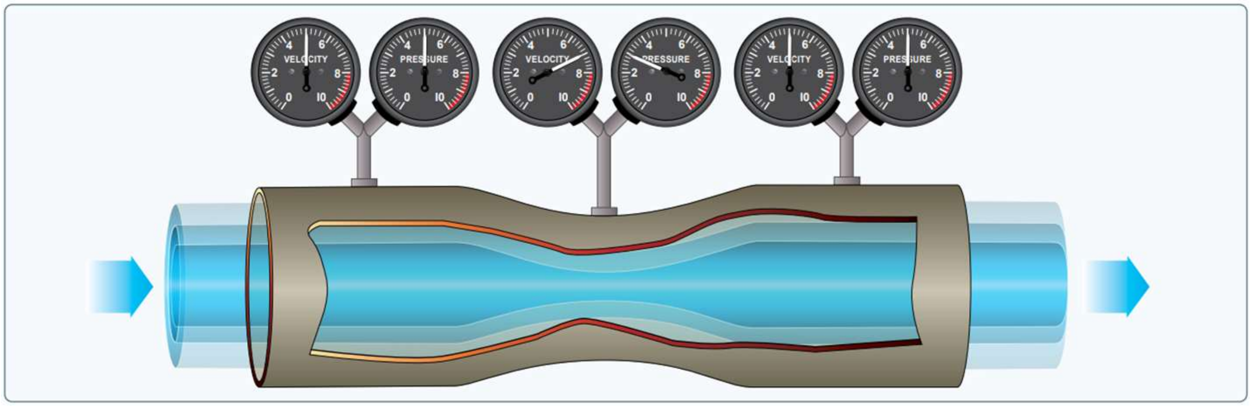
Law of Conservation of Energy: energy is always conserved.

Not on Exam

Bernoulli's Principle

- Comes from conservation of energy
- Potential energy+kinetic energy+work done=constant
  - mass x gravity x height + ½ mass x Velocity^2 + pressure x volume = const.
  - $mgh+1/2mV^2+pv=const.$
    - Assume density is constant, and divide by volume
    - mass/volume = density, ρ
- $\rho gh+1/2\rho V^2+p=constant$

Venturi (Classic Bernoulli)

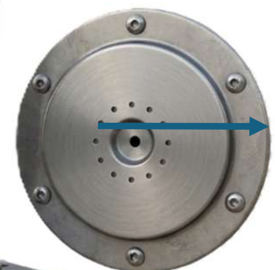


- Mass flow through the tube is constant, when tube narrows speed increases (density x area x Velocity=const.)
- Bernoulli: $\rho gh+1/2\rho V^2+p=\text{constant}$
  - Horizontal, h=constant: $1/2\rho V^2+p=\text{const.}$

As the flow velocity increases, the pressure must decrease

Reminder: Airspeed Indicator

$1/2\rho V^2 + p$



p

- Flow brought to a stop
- All velocity converted to pressure
- Dynamic pressure: $1/2\rho v^2$
- Pitot tube feels: $1/2\rho v^2 + p$

- Flow slides by static port
- Static board measures static pressure (pressure of still, ambient air)
- Static pressure: p

Airspeed indicator measures the difference between stagnation and static pressure: $1/2\rho V^2$

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Newton's Laws of Motion

1. Every object persists in a state of rest or uniform motion in a straight line unless acted upon by an external force
2. Force equals mass times acceleration ($F = m \times a$)
3. For every action there is an equal and opposite re-action

Four Forces of Flight

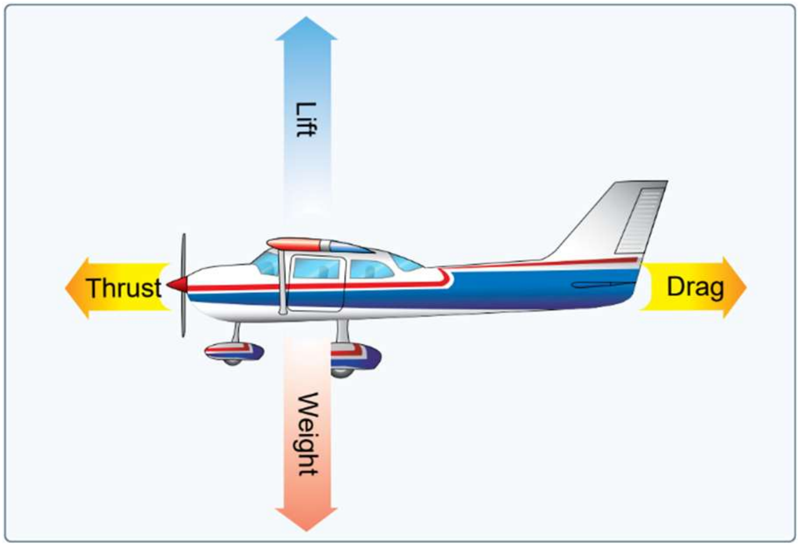
Lift:
Upward force due to the effects of airflow over/under the wing
Lift acts perpendicular to the relative wind (definition)

Weight:
Opposes lift, caused by the downward pull of gravity

Thrust:
Forward force propelling the aircraft through the air

Drag:
Opposes thrust, backward force limiting airplane speed

Drag acts parallel to the relative wind (definition)



Airfoil Definitions

Camber

- Curvature of the upper/lower surface

Leading / Trailing Edge

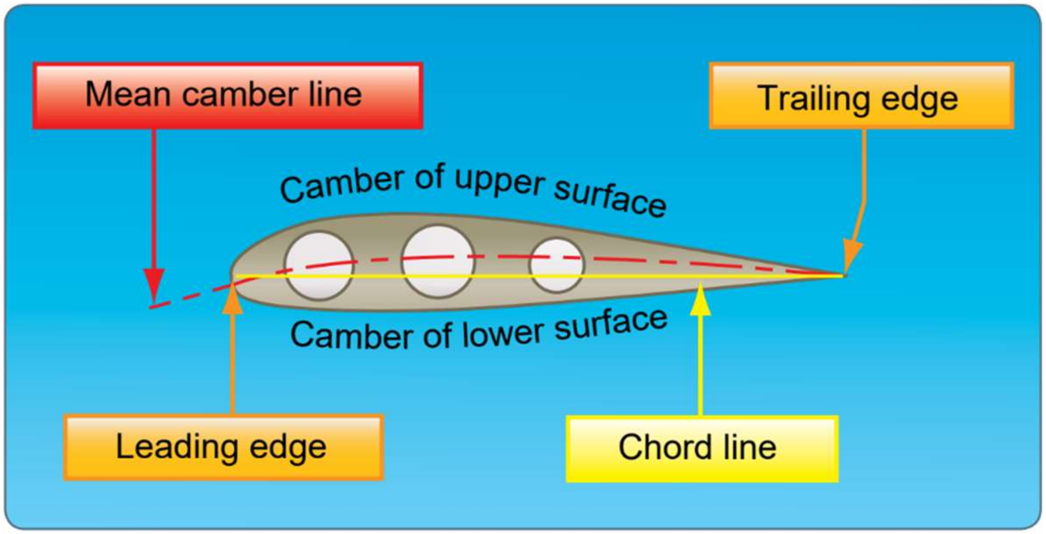
- Generally, rounded leading edge
- Generally, narrow & tapered trailing edge

Chord Line

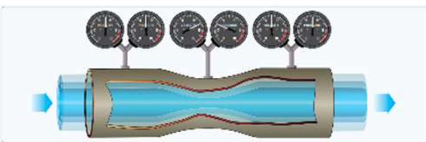
- Straight line drawn through the airfoil connecting the leading and trailing edges
- Distance of chord line to the upper & lower surfaces denotes camber

Mean Camber Line

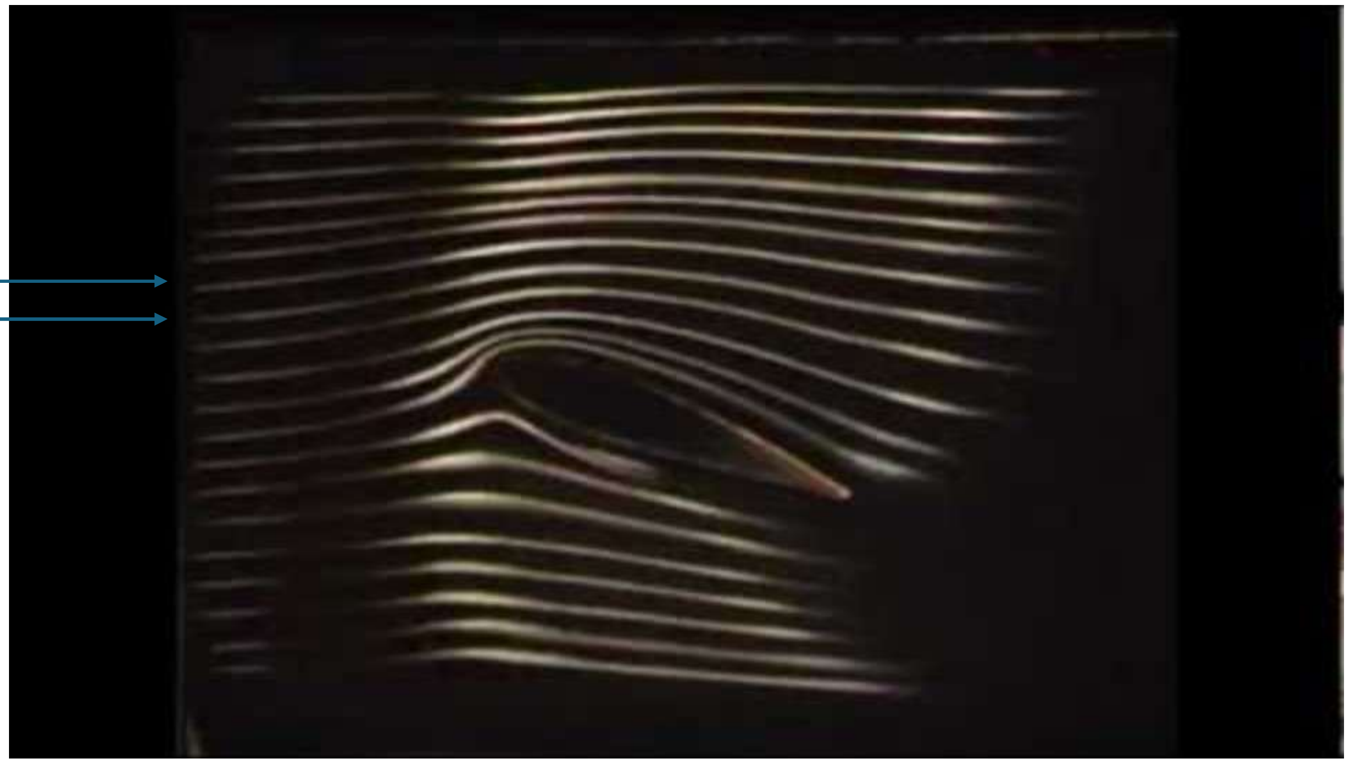
- Equidistant at all points from the upper and lower surfaces



Aerodynamics



These streamlines are effectively venturis



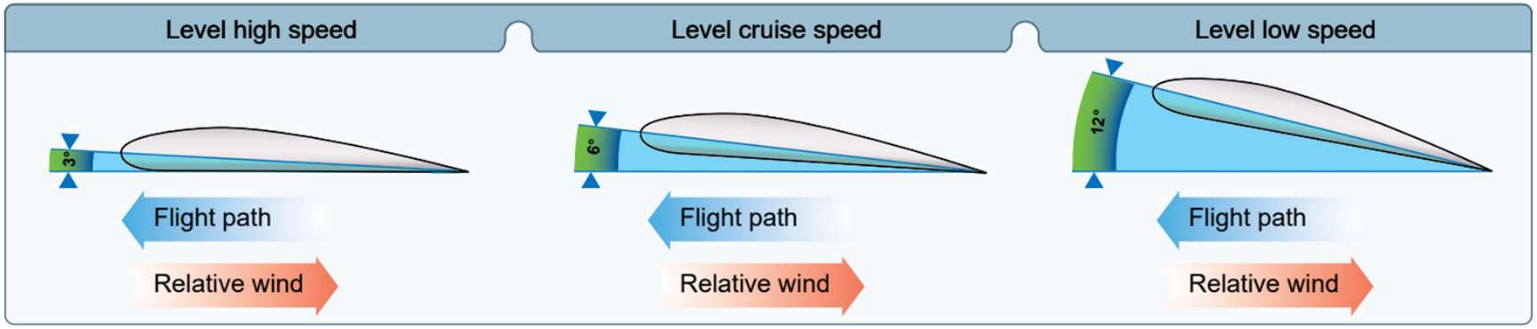
https://www.youtube.com/watch?v=UqBmdZ-BNig

Angle of Attack

Chord Line:
Imaginary straight line joining the leading and trailing edges of an airfoil

Relative Wind:
Direction of movement of the wind relative to the aircraft's flight path

Angle of Attack:
Angle between the chord line and the relative wind



Aerodynamic Stall

https://youtu.be/SiOiVHUEYao

Wing Planform (Area = S)

Planform: Outline of the wing from above

- Varies with desired aerodynamic characteristics

Taper - Ratio of chord from root to tip

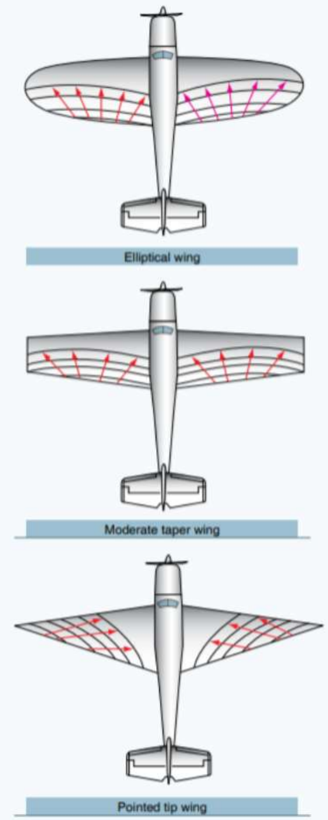
- Generally, decreases drag / increases lift
- Reduces weight of wing

Aspect Ratio (AR) – Ratio of wingspan to chord

- Higher AR decreases drag, and vice versa
- Low AR for extreme maneuverability & strength

Sweep – Slant of the wing

- Usually rearward, but can be forward
- Helps with lateral stability in low-speed planes

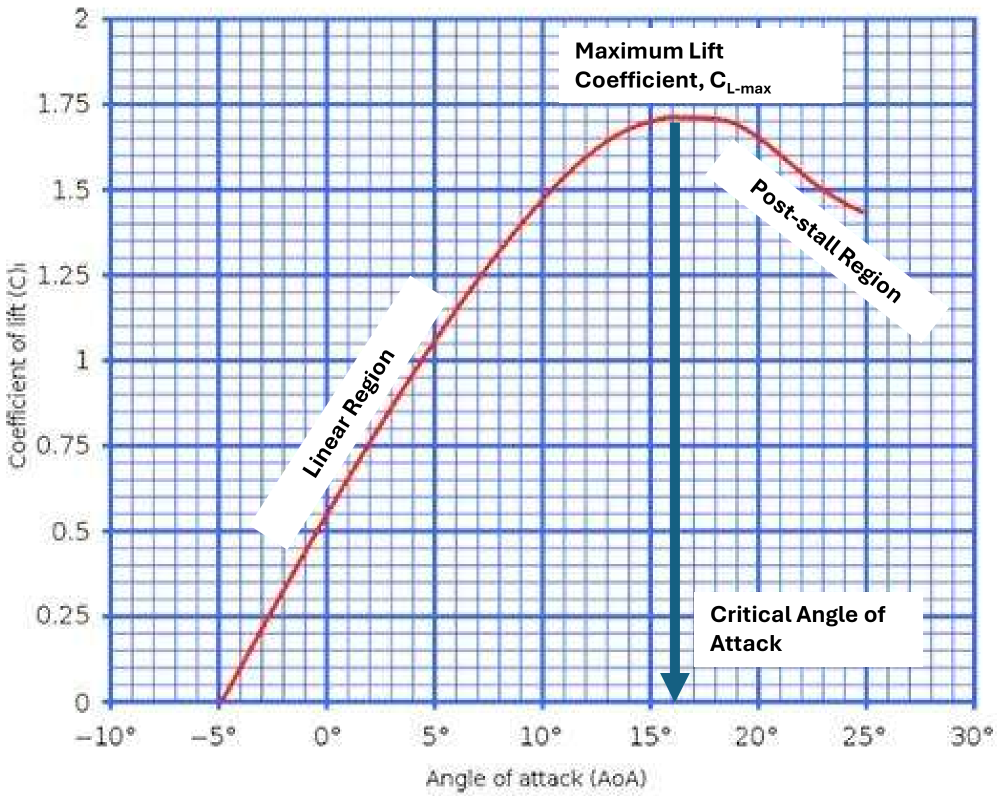


Definition of Lift Coefficient

- $C_L = \frac{L}{\frac{1}{2}\rho V^2 S}$ (this is a definition)
  - L = lift (lift force generated)
  - $1/2\rho V^2$ is dynamic pressure
  - S is the area the pressure can action
  - Note: pressure x area is force, so fraction is force/force (not units)

- There is also a drag coefficient:
- $C_D = \frac{D}{\frac{1}{2}\rho V^2 S}$

Lift and Angle of Attack are Related



- **Lift increases linearly with angle of attack near stall**
- **Stall occurs at the critical angle of attack regardless of airspeed, aircraft weight, etc.**

Airfoil Design

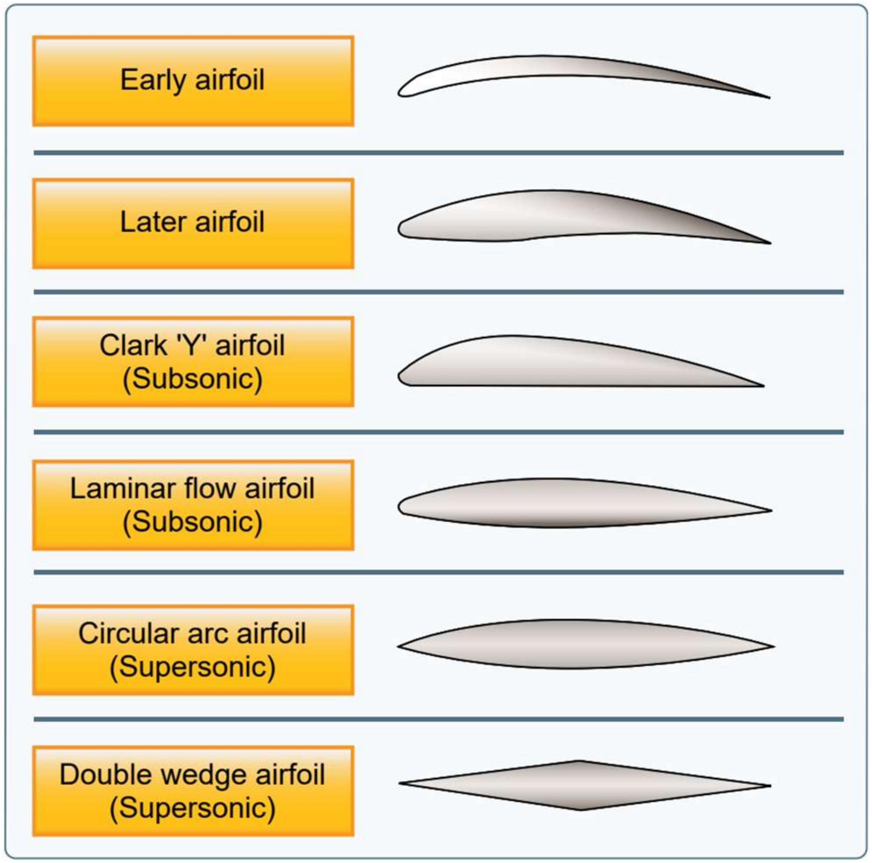
Low Pressure Above

- Faster moving air (Bernoulli)
- Downwash (Newton's 3rd Law)

High Pressure Below

- Air Deflection (Newton's 3rd Law)
- Stagnation Point (Bernoulli)

Aircraft weight, speed, and purpose dictate airfoil design



An airfoil is a slice through the planform, the angle of incidence and the shape can vary spanwise

Airfoil Design, Pressure Distribution

Pressure varies with AOA

Stagnation point

- Location where air splits above and below the airfoil
- Pressure is maximum, dynamic+static, flow “stops” and velocity is converted to pressure

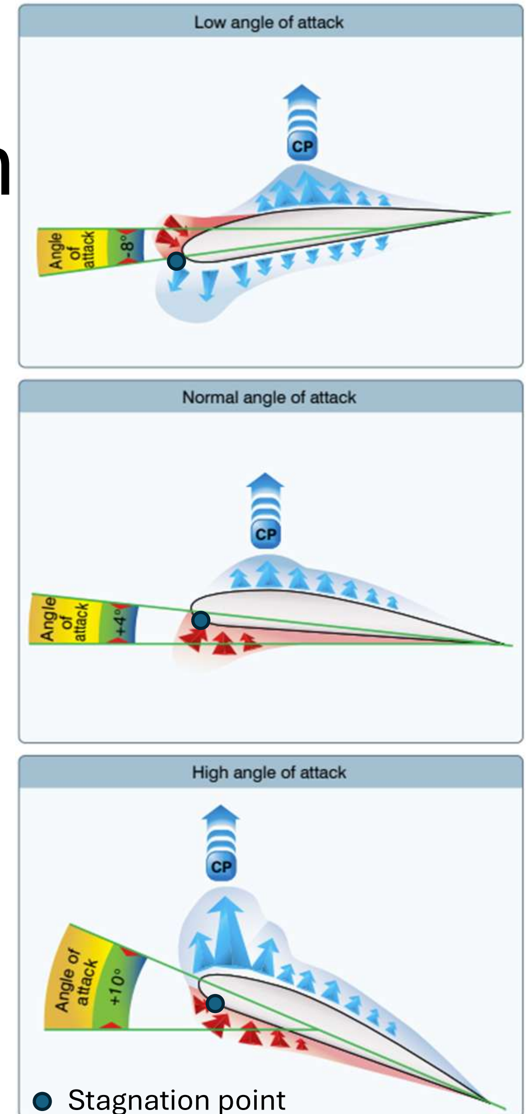
Center of Pressure (CP)

- Average of the pressure variations at a given AOA
- Higher AOAs: CP moves forward
- Lower AOAs: CP moves aft

Streamline Curvature

- The more curved the flow, the more negative the pressure
- Stagnation point (high pressure) where the flow divides or comes together

Affects aerodynamic balance & controllability



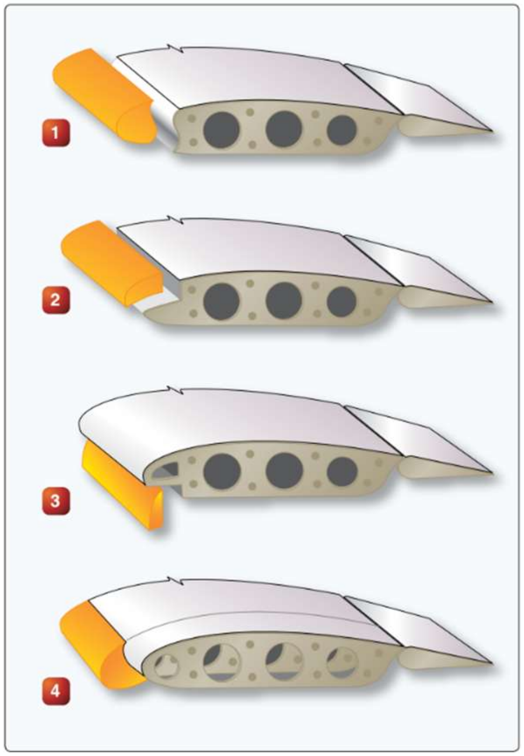
High Lift Devices

Slot

Slat

Flap

Cuff



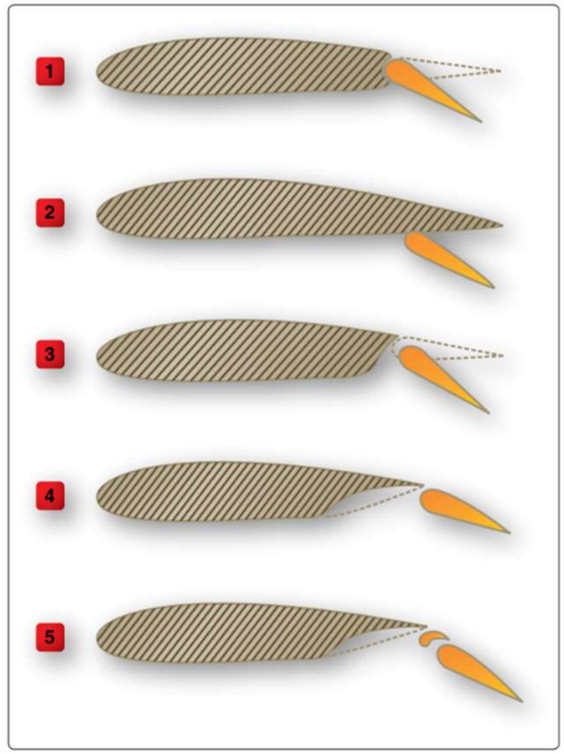
Plain Flap

Split Flap

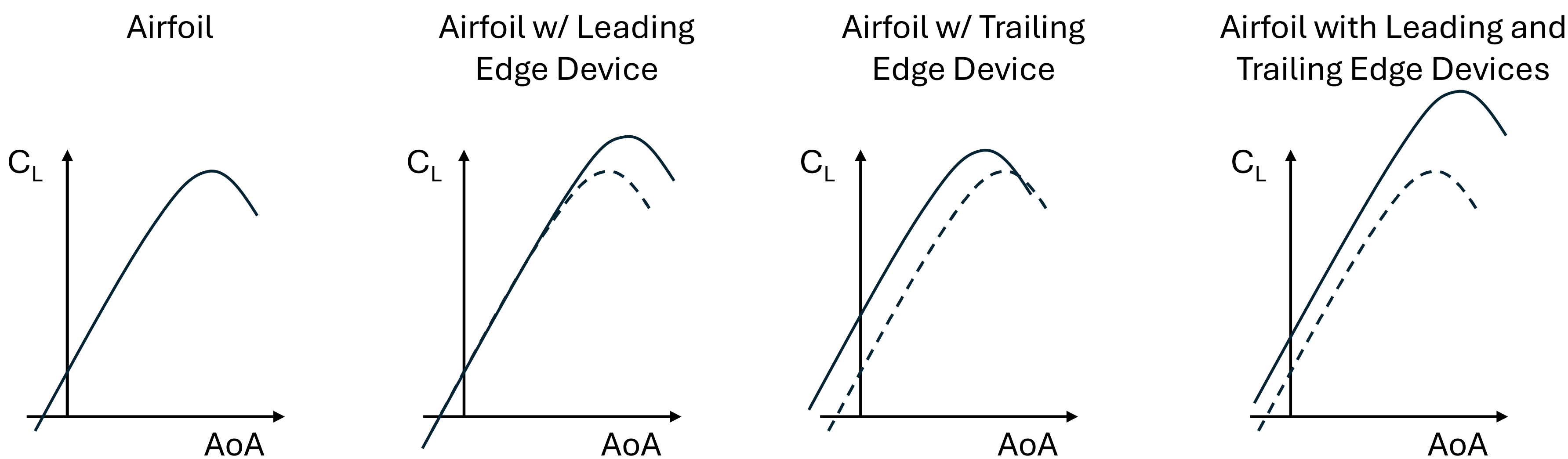
Slotted Flap

Fowler Flap

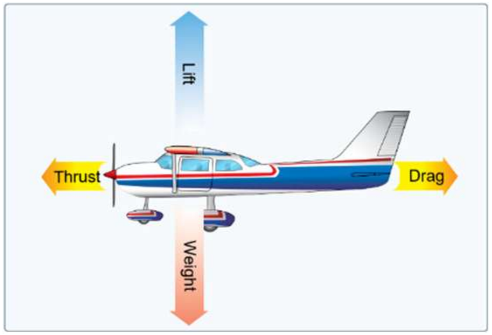
Double Slotted



Effect of High-lift Devices



Types of Drag



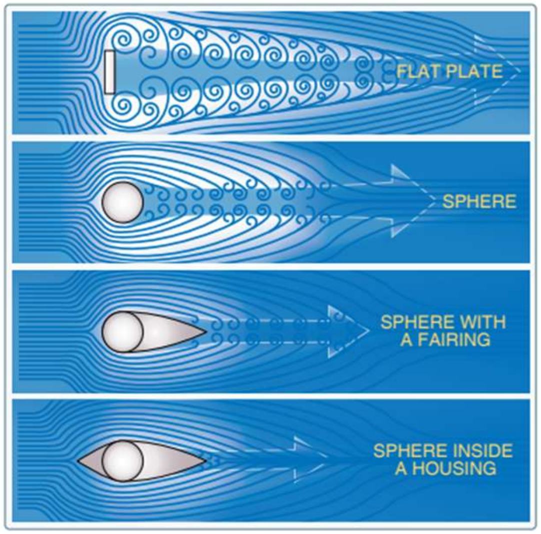
Parasite Drag:
Surfaces interfering with smooth airflow

- Form: Aircraft size & shape
- Interference: Currents of air interacting
- Skin Friction: Airplane's surface

Induced Drag:
Byproduct of lift

- Caused by creation of wingtip vortices and associated downwash

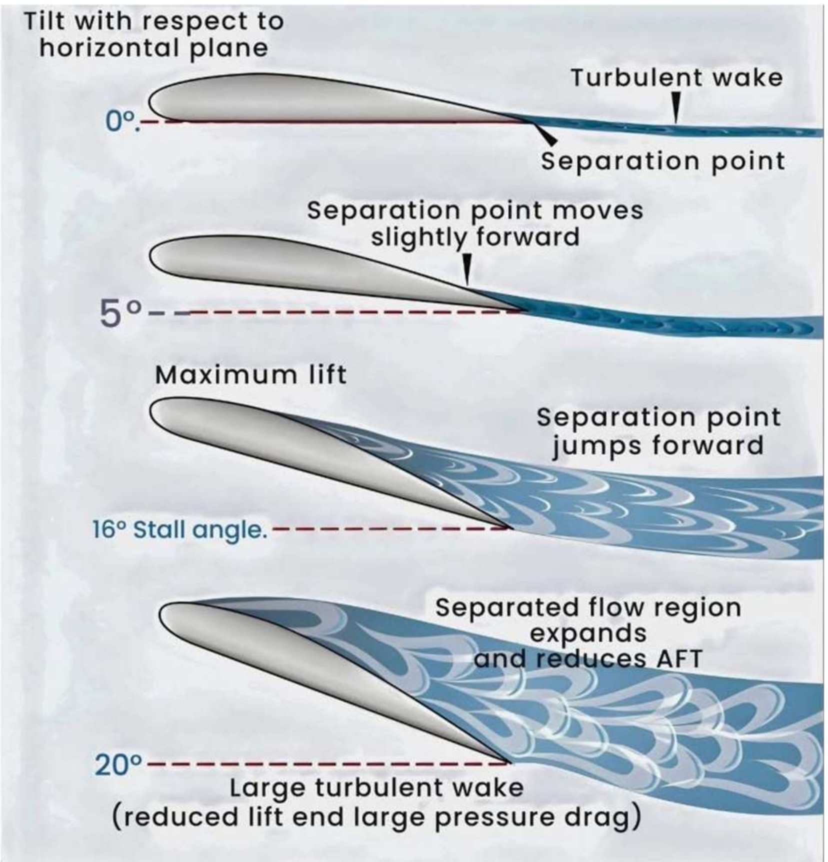
Parasite Drag

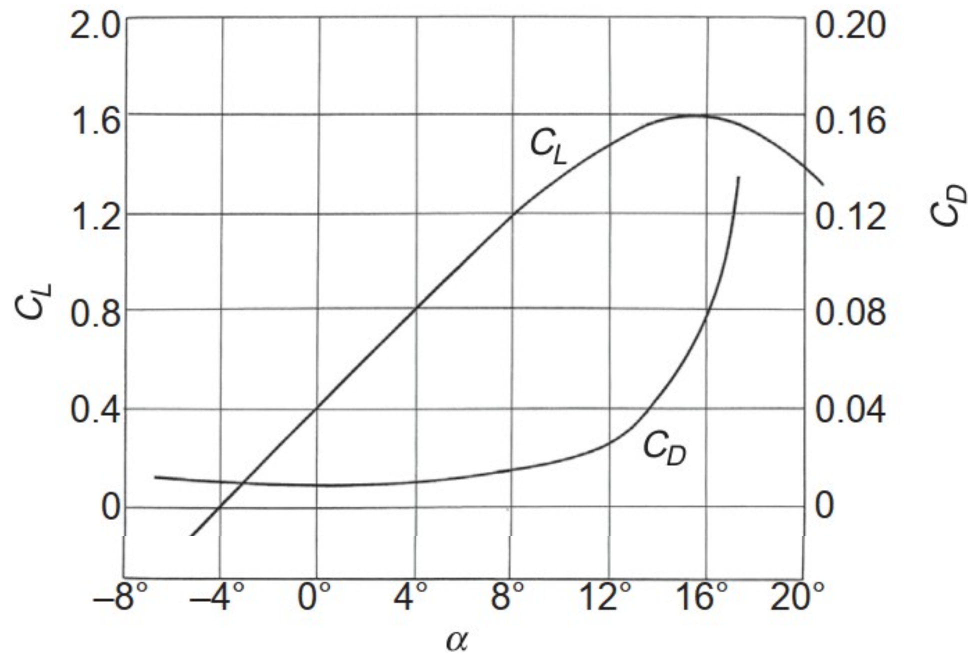


Induced Drag

- **Fundamentally, the airplane is pulling ("dragging") air along with it (think of a bus pass by you)**
- **If the air remained undisturbed after the airplane passed there would be no drag force**

Airfoil Drag





Total Drag

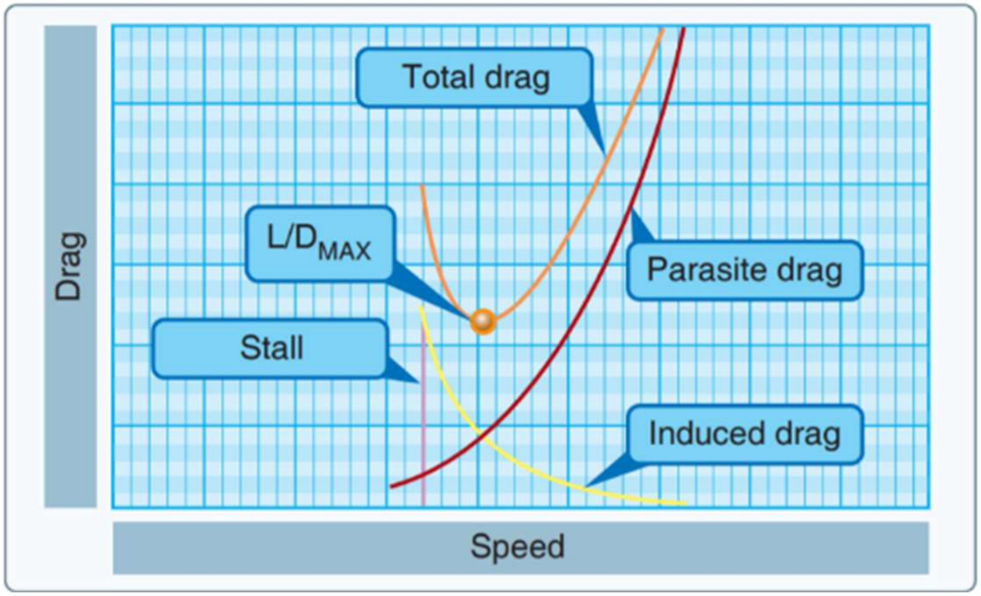
Total Drag = Parasitic Drag + Induced Drag

Region of Normal Command

- As airspeed decreases, total drag decreases to a point

Region of Reversed Command

- Below this point, drag begins to increase
- Slower airspeeds require higher thrust



Not on Exam

Math on Drag: Velocity^2

- Downwash rotates lift direction aft (aligned with drag) – induced upwash changing relative wind
- Induced Drag: $C_{DI}=C_L^2/\pi eAR$
  - e – efficiency factor (0.99 for elliptical planform, 0.85 for rectangular)
  - Reminder: $C_L = \frac{L}{\frac{1}{2}\rho V^2 S}$
  - Lift=Weight (const.) C_L decreases with V^2
- Parasitic Drag: C_{DP}=const.
- $C_{D\text{-total}}=C_{DP}+C_{DI}$
- Drag=$1/2\rho V^2 S C_{D\text{-total}} = \frac{1}{2}\rho V^2 S C_{DP} + \frac{W^2}{\frac{\pi}{2}\rho V^2 SeAR}$

AR = 33.5

Schleicher ASH 31
Glider

AR = 5.6

Piper
Cherokee

Total drag is a parabola, parasitic drag increases with V^2, but induced drag decreases with V^2

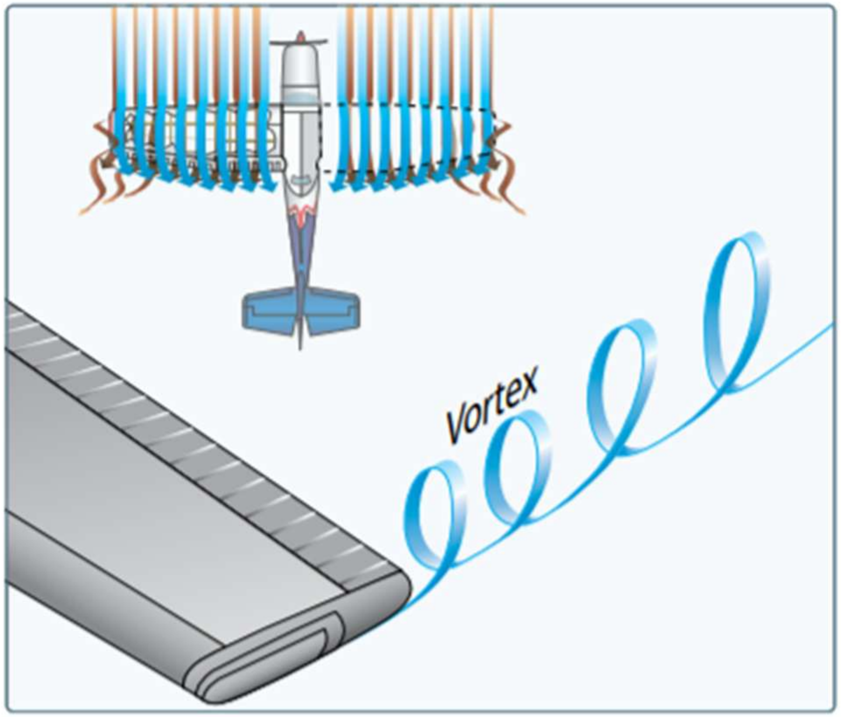
Wingtip Vortices

Why they Occur

- Occur whenever an airfoil is producing lift
- Difference in pressure above and below the wing results in fast spinning vortices spiraling off each wingtip
- Increase induced drag due to energy spent producing the turbulence

Strength

- Greater the AOA, the stronger the vortices
- Strongest: Heavy, clean, and slow
  - Heavy: maximum weight, like at takeoff with full fuel
  - Clean: no high-lift devices
  - Slow: low-air speed (maximum C_L)



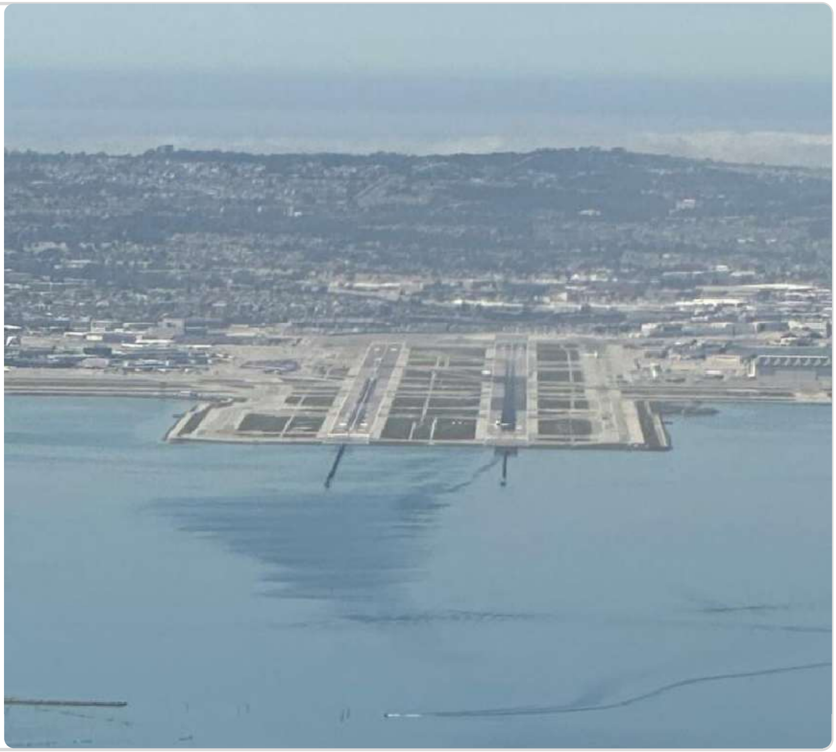
Wingtip Vortices (cont.)

Vortex Behavior

- Sink at several hundred feet per minute
- At the ground, tend to move with the wind
- Crosswind
  - Decreases movement of the upwind vortex
  - Increases movement of the downwind vortex
- Tailwind
  - Can move vortices into the touchdown zone

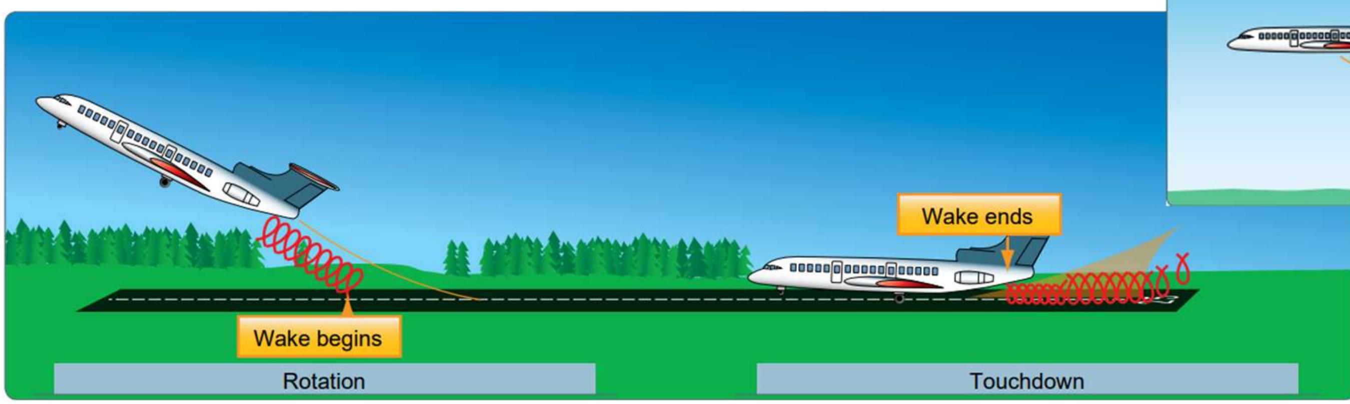
Picture

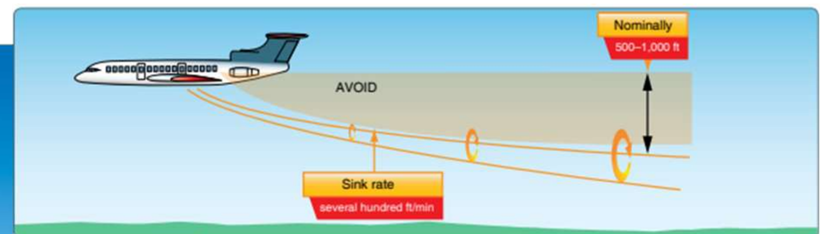
- Visible vortices in the water (SFO 28R)
- Crosswind from the right blowing the vortices to the left



Avoiding Wingtip Vortices

- **Takeoff before a prior aircraft's rotation point, climb above their flight path (or turn before penetrated)**
- **Takeoff after a landing jet's touchdown point**
- **Land prior to a departing aircraft's takeoff point**
- **Stay above a preceding aircraft's path, land beyond their touchdown point**
- **En Route: Avoid flying through another aircraft's flight path within 1,000'**





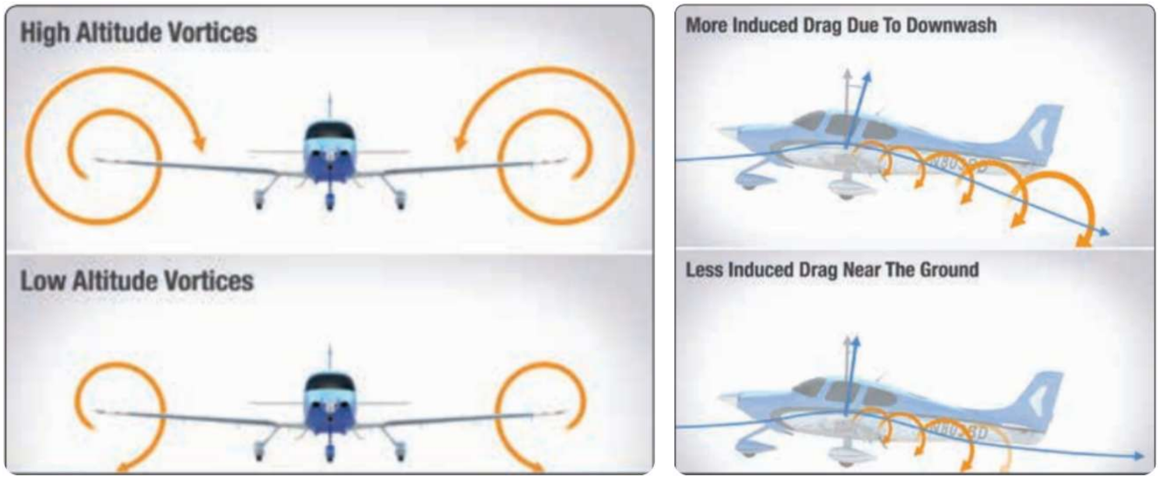
Ground Effect

Reduces induced drag

- Vertical component of the airflow around the wing is restricted by the ground

Effects on Flight

- Takeoff: Capable of lifting off at a lower-than-normal speed
- Landing: Airplane seems to float in ground effect

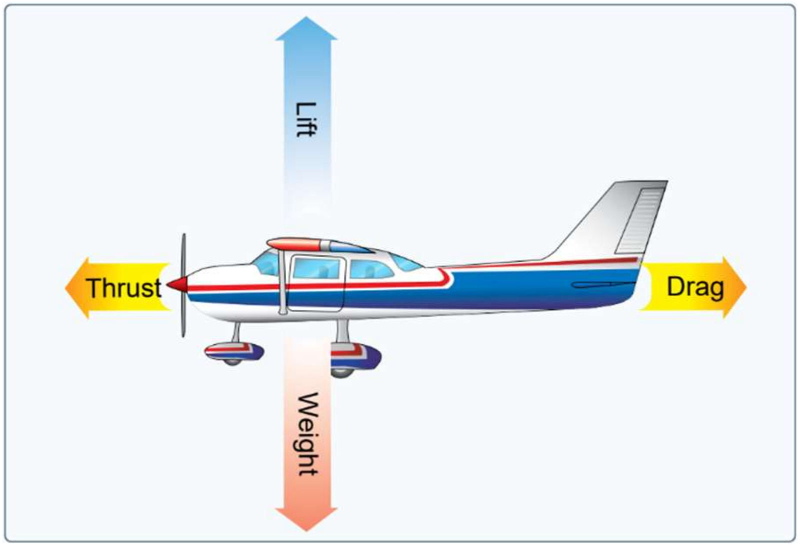


Ground effect reduces downwash/upwash, lift vector is more vertical, more effective lift and less drag

Forces of Flight: Weight

Force of gravity acts vertically through the CG toward the center of the earth

Weight always pulls towards the center of the earth



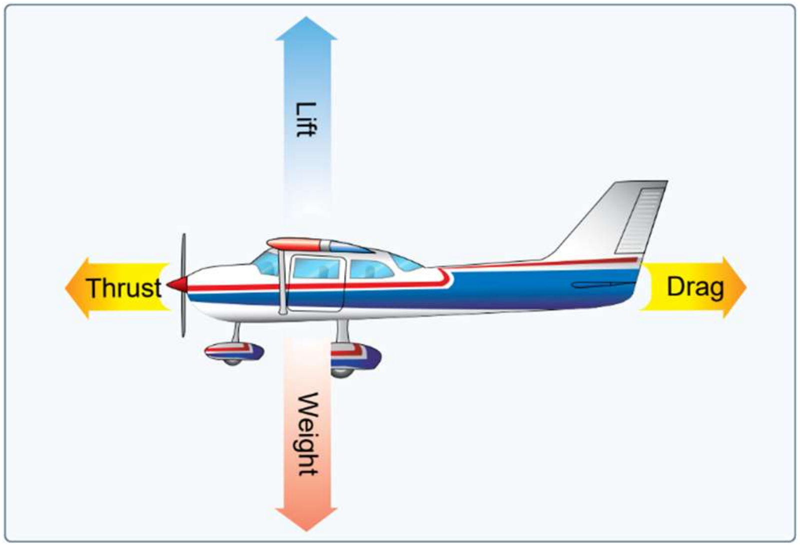
Forces of Flight: Thrust

Forward force which opposes drag

- Newton's first law, if thrust=drag and Lift=weight, altitude and airspeed remain constant

Airplane will continue to accelerate until thrust is equal to drag

- If thrust is > drag, the plane accelerates
- If thrust is < drag, the plane decelerates
- Newton's second law, Force = Mass x Acceleration



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- Fundamentals of aerodynamics
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- Stability
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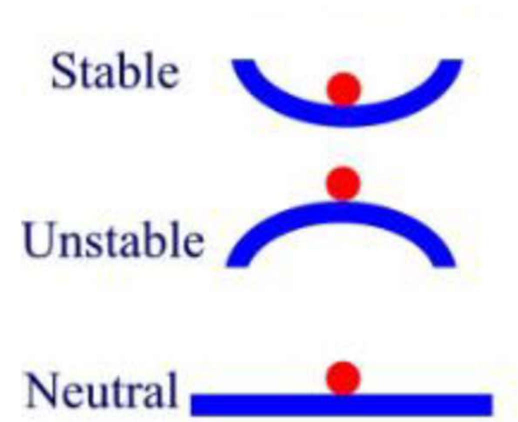
Static Stability

- Positive (stable)
  - Ball returns to starting position when disturbed
- Negative (unstable)
  - Ball moves away from starting position when disturbed
- Neutral
  - Ball remains in new position when disturbed



Dynamic Stability

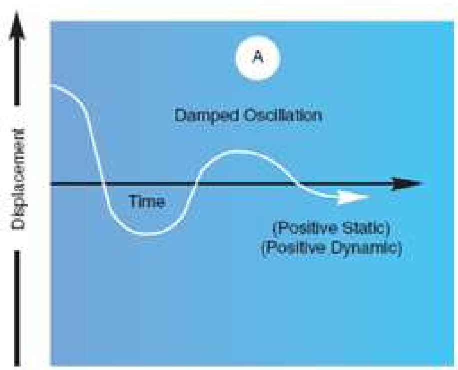
Inherent quality to correct for disturbances & return to the original flight path

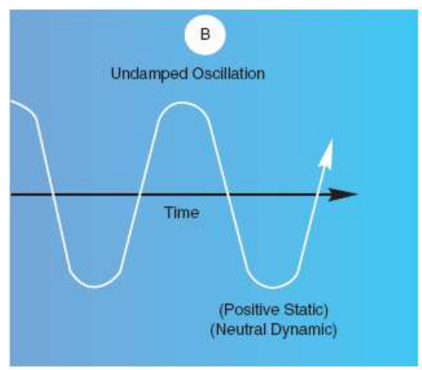
Static Stability: Aircraft's initial tendency when disturbed

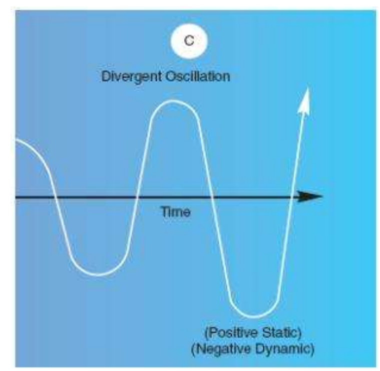
- Positive: Returns to original state, Negative: Trends away from original state, Neutral: Remains in new condition

Dynamic Stability: Aircraft's response over time when disturbed

- Positive, Negative, & Neutral – same as Static Stability, but over time
- Damped, Divergent & Undamped Oscillations

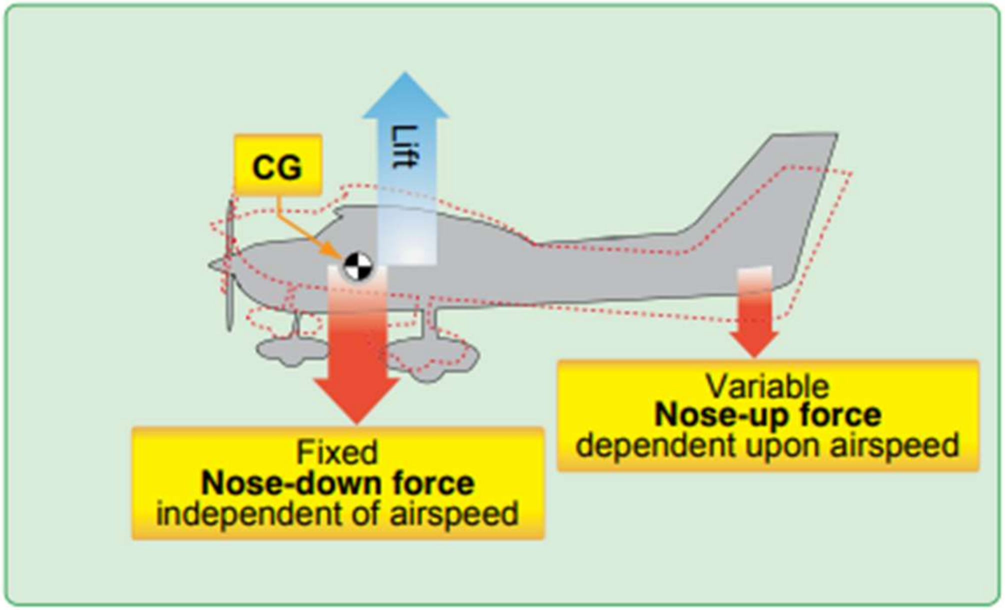




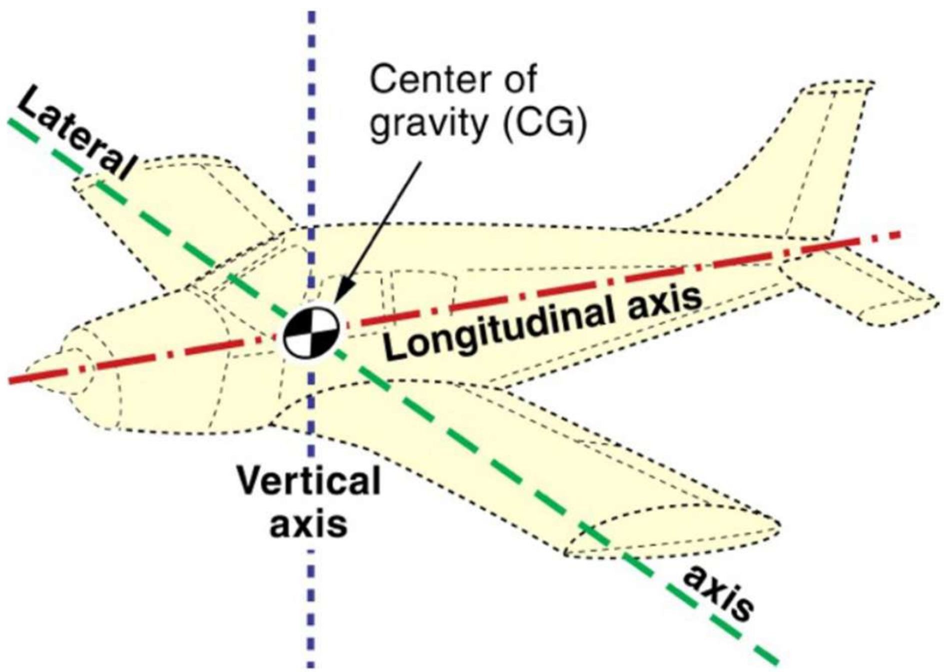


Significantly affects Controllability & Maneuverability

Weight and Balance



Axes of an Airplane



Longitudinal Stability

About the Lateral Axis (Pitch)

In a stable aircraft, if the plane is nosed down, the wing & tail moments bring the nose back up

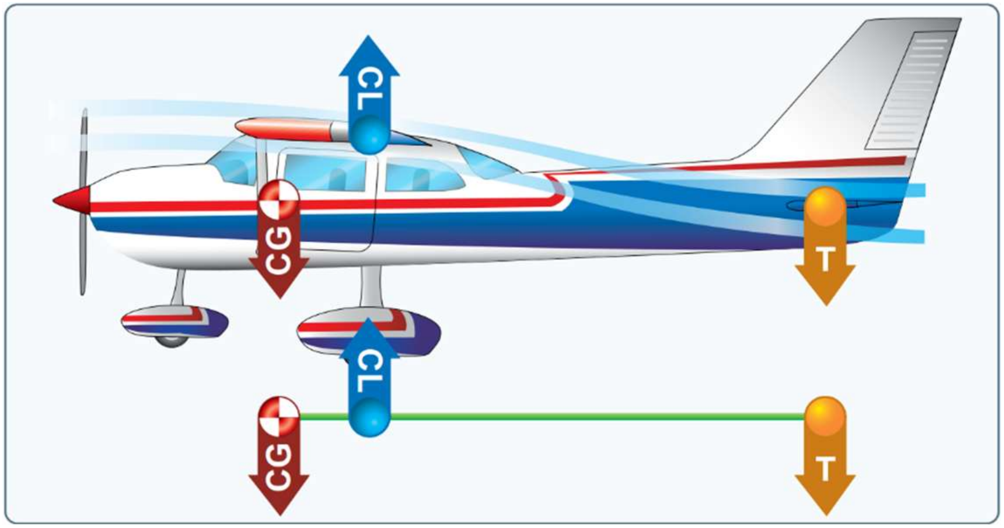
- And vice versa

Dependent on 3 factors

- Location of the wing relative to the CG
- Location of the horizontal tail relative to the CG
- Size of the tail surfaces

More stable:

- Forward CG
- Bigger and more aft tail



Lateral Stability

About the Longitudinal Axis (Bank)

Dihedral

- Upward angle of the wings from root to tip

Sweepback

- Basically, increases effects of dihedral
- 10 degrees of sweepback ≈ 1-degree of dihedral

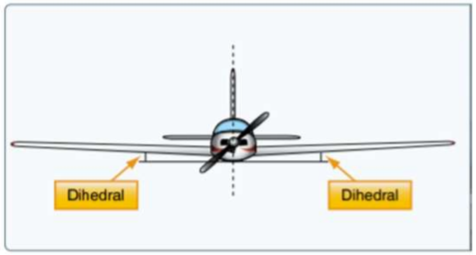
Keel Effect

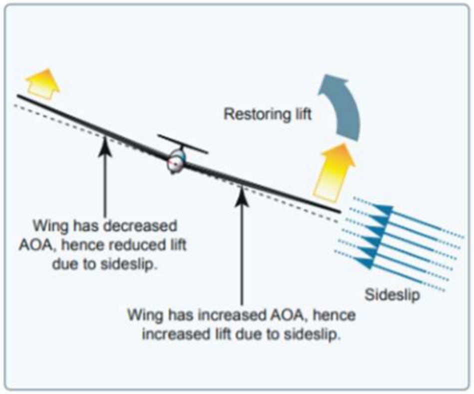
- Greater portion of the keel is above & behind the CG

Weight Distribution

- Plane will bank toward heavier loaded side

Dihedral



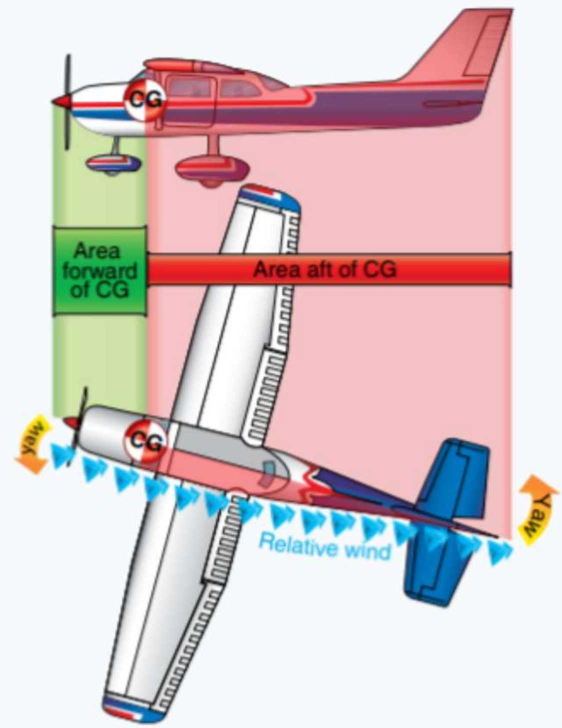


Keel Effect

Directional Stability

About the Vertical Axis (Yaw)

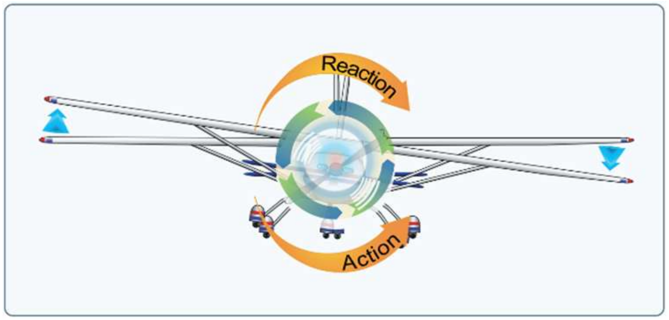
- **Area of the vertical fin and fuselage aft of the CG**
- **Acts like a weathervane, nose points into the wind**



Left Turning Tendencies (1-2 of 4)

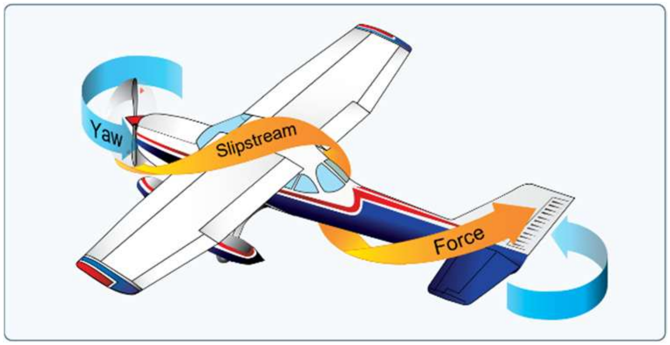
Torque Reaction

- Newton's 3^{rd} Law
- Engine parts/propeller rotate right, equal force rotates the plane left



Corkscrew Effect (Spiraling Slipstream)

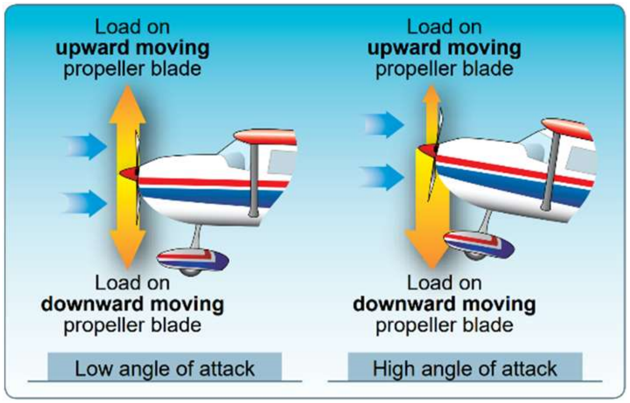
- Prop rotation sends air spiraling aft, striking left side of vertical stab



Left Turning Tendencies (3-4 of 4)

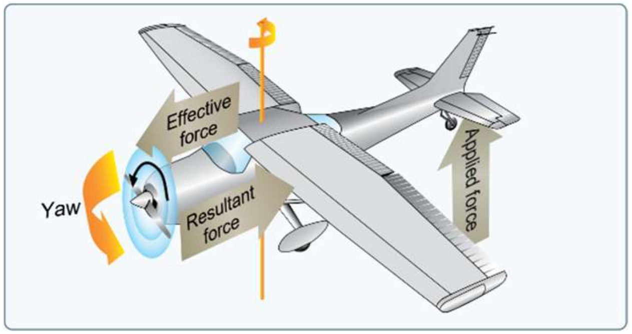
P-Factor (asymmetric loading)

- Descending prop blade takes a bigger bite of air than the ascending blade



Gyroscopic Action

- Precession
- Most prominent in tail wheel aircraft when tail is raised for takeoff



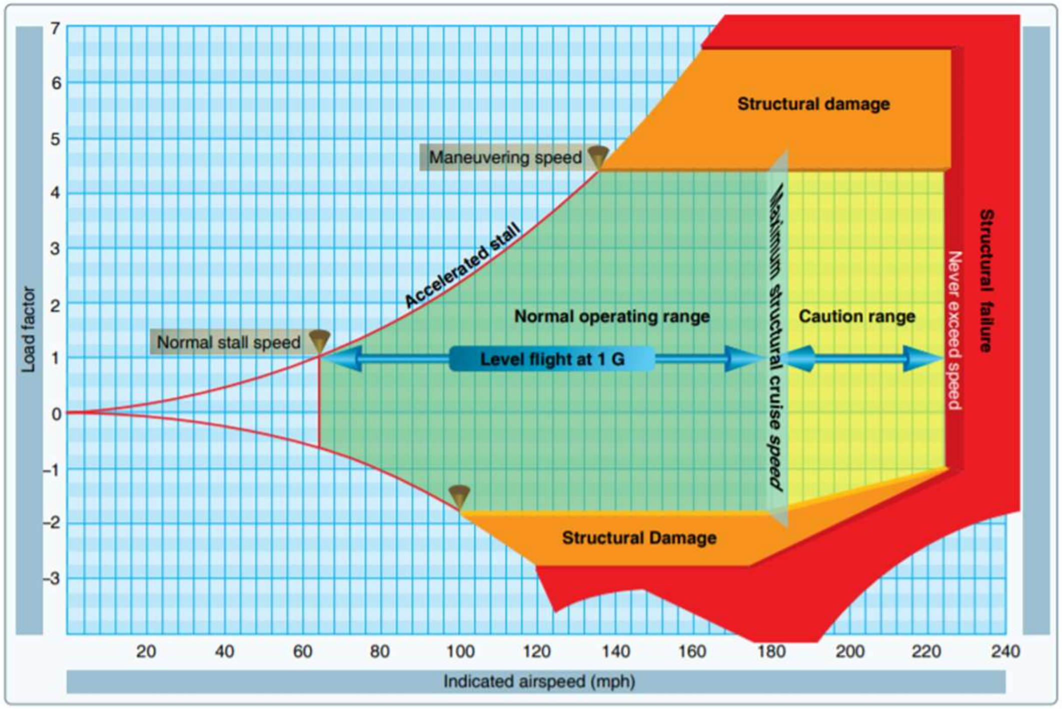
Load Factors

Ratio of the total lift to the gross weight of the plane

- Measured in Gs

Why it's important

- Possible to overload the aircraft structure
- Increasing load factor increases stall speed



Newton's 2nd law, load factor is acceleration, so a large force is supported by the wings

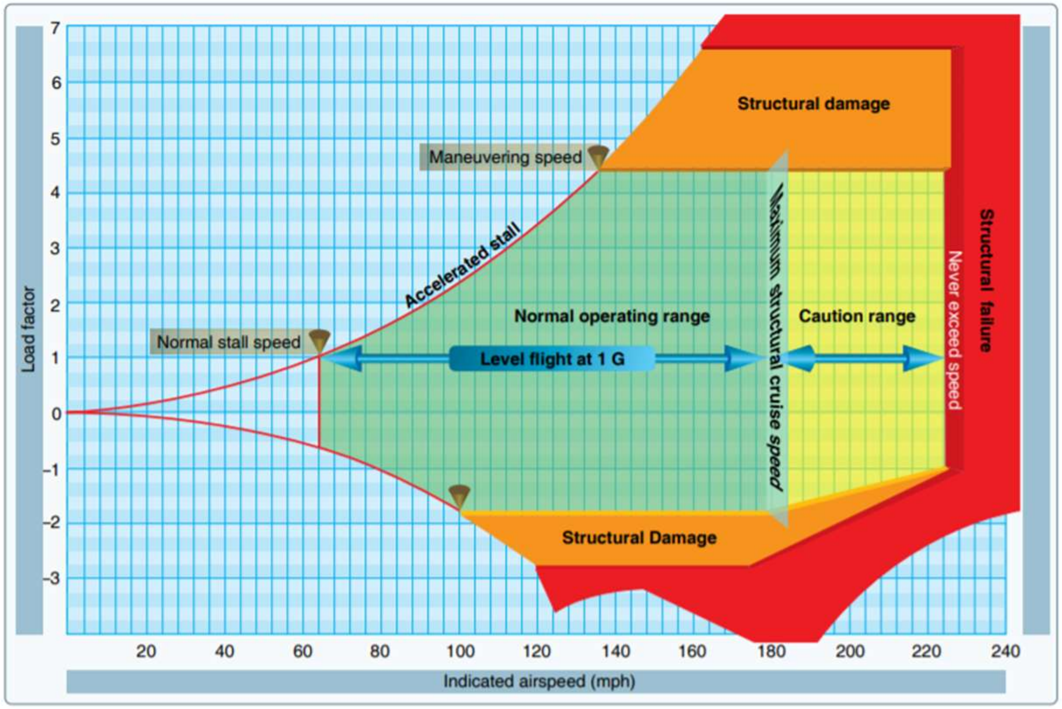
Load Factors (cont.)

Airplane Design

- Designed to operate within limits
- Normal: -1.52 to 3.8 Gs
- Utility: -1.76 to 4.4 Gs
- Acrobatic: -3 to 6 Gs

Vg diagram

- Lines of Maximum Lift Capability
- Maneuvering Speed
- Intersection of Negative Limit Load Factor & Line of Maximum Negative Lift Capability
- Limit Speed



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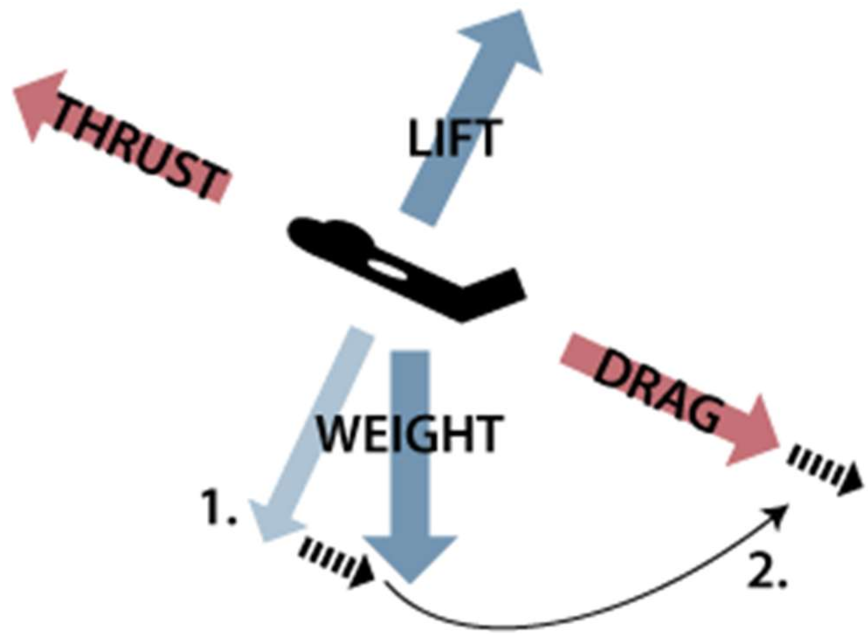
- Stalls and Spins

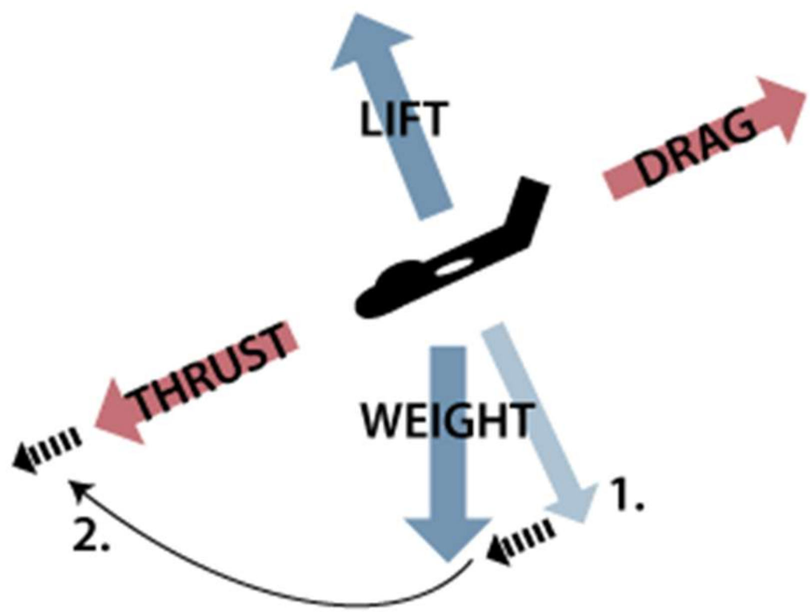
Climbs: Climb Airspeed

- **With no change in thrust, airspeed will decrease in a climb**
- **When inclined upward, a component of weight acts rearward and has the same effect as drag**
- **Additional thrust is required to maintain airspeed**
- **Newton's 2^{nd} Law:**
  - For constant airspeed: the sum of forces in vertical direction and sum of forces in horizontal direction must equal zero
  - Note: Lift, thrust, and drag have both vertical and horizontal components



Descents: Descent Airspeed

- **With no change in thrust, airspeed will increase in a descent**
- **A component of weight acts forward and has the same effect as thrust**
- **Power must be reduced to maintain airspeed**
- **Newton's 2nd Law:**
  - For constant airspeed: the sum of forces in vertical direction and sum of forces in horizontal direction must equal zero
  - Note: Lift, thrust, and drag have both vertical and horizontal components



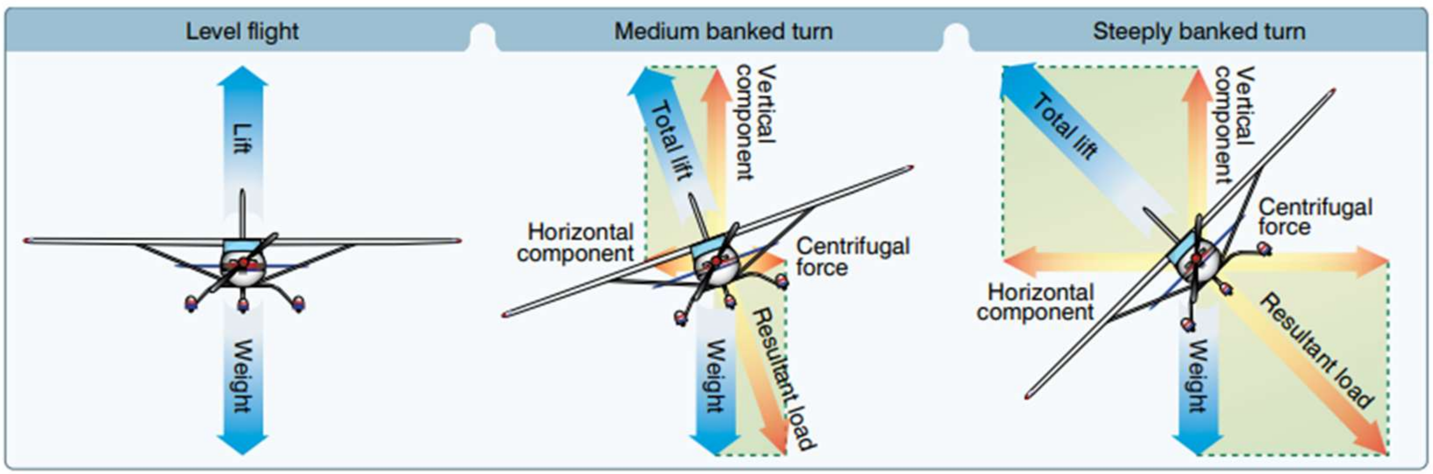
Turns: Lift and Angle of Attack

Lift is divided into a Horizontal & Vertical component

- Vertical: Acts vertically, opposite weight
- Horizontal: Makes the plane turn (centripetal force)

AOA in a Turn

- Vertical lift is reduced while weight remains the same
- AOA must be increased so the vertical component of lift equals weight
- Increased AOA increases drag. Power is required to maintain speed



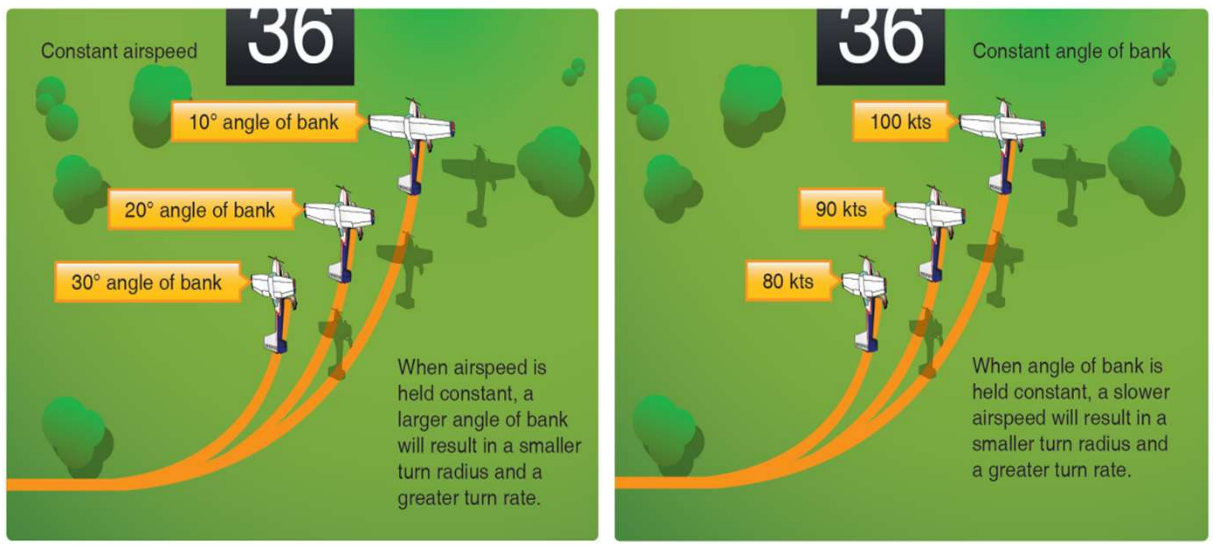
Turns: Rate and Radius

Rate of Turn

- Varies with horizontal component of lift (bank)

Turn Radius

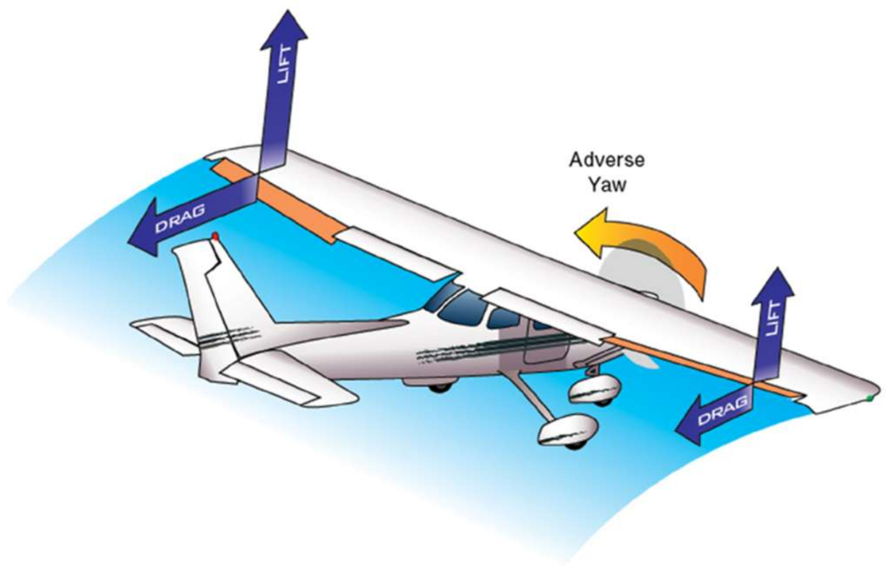
- Varies with airspeed & bank angle



Lower airspeed and steeper bank result in shorter/faster turns

Adverse Yaw

- Induced drag
  - Increase in lift = increase in drag
  - Parasitic drag from aileron
- If we want to roll right
  - Yoke turns to the right
  - Right aileron goes up, left aileron goes down
  - Left wing develops more lift, therefore more drag
  - Airplane yaws in opposite direction to roll



Turns: Coordination

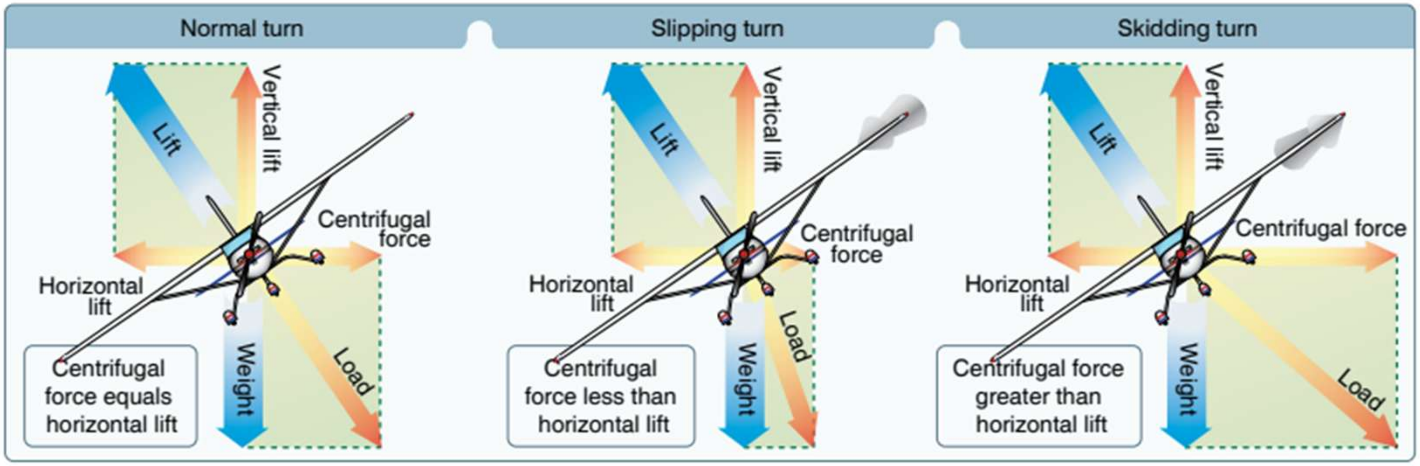
Coordinated Turn: Horizontal Component of Lift = Centrifugal Force

Slipping Turn: Rate of turn is too slow for the bank angle

- Horizontal component of lift is greater than centrifugal force

Skidding Turn: Rate of turn is too great for the bank angle

- Centrifugal force is greater than the horizontal component of lift



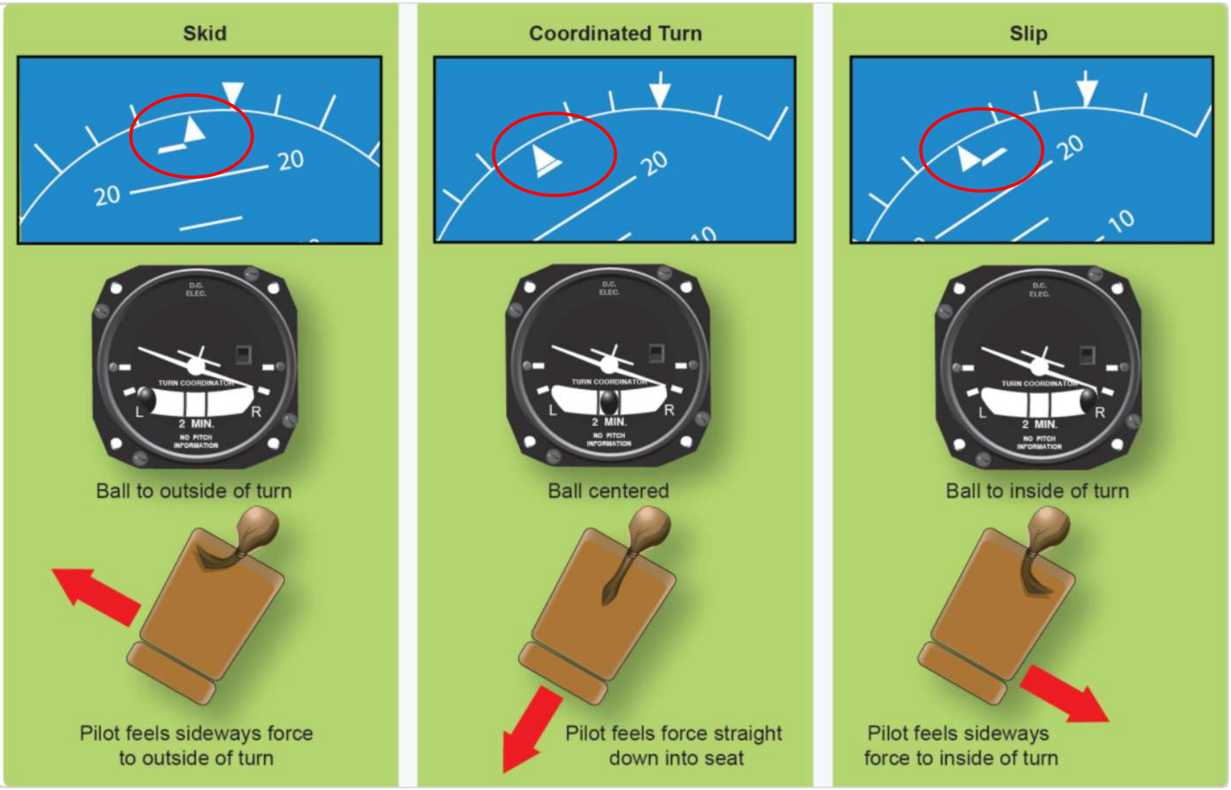
Turn and Slip Indicator

Coordinated rudder & aileron should be used in all turns

Use the Turn Coordinator

- Step on the ball to center it

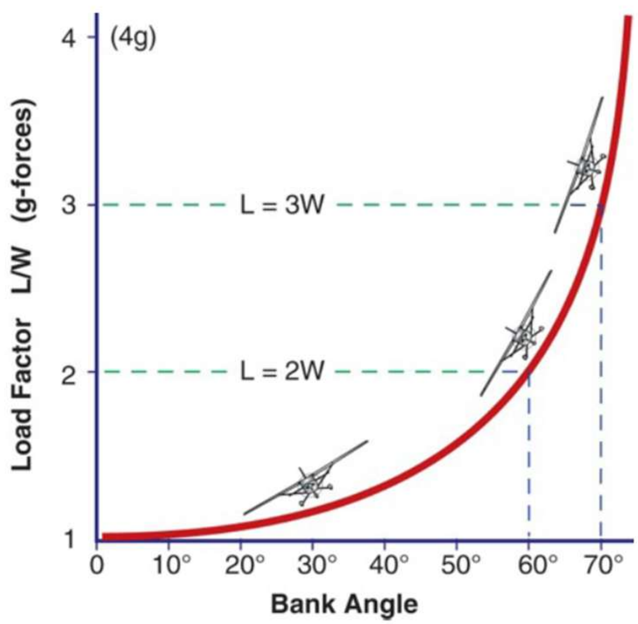
Uncoordinated flight results in excess drag & decreased performance

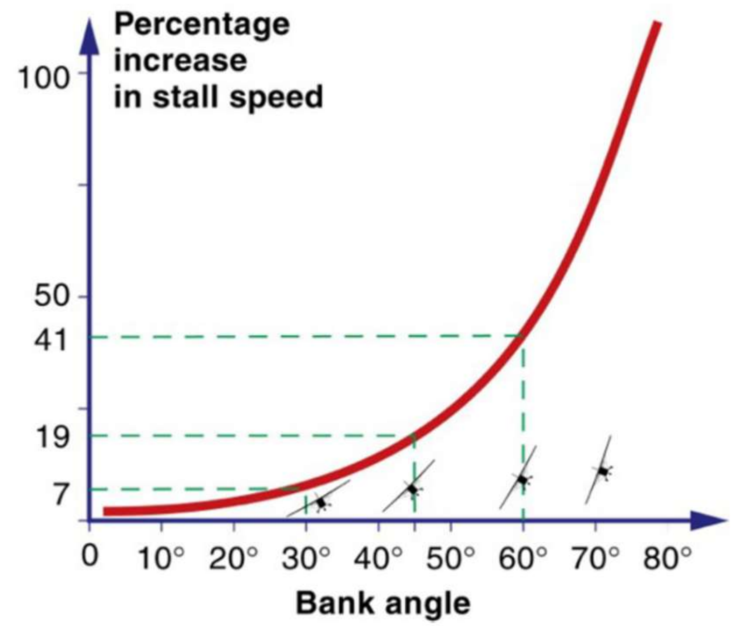


The ball represents the tail of the airplane

Load Factor vs Bank Angle

(For a level term)





Outline

- Fundamentals of aerodynamics
- Forces of flight
- Stability
- Manuevering flight
- Aircraft Performance
- Stalls and Spins

Performance Definitions

Kinetic Energy (KE): Energy of Speed

- Directly proportional to the square of airspeed

Potential Energy (PE): Stored Energy

- Directly proportional to altitude

Power & Thrust

- Thrust: Force or pressure exerted on an object (pounds or newtons)
  - Typically thrust is constant for a jet engine with speed variations
- Power: Measurement of the rate of performing work (hp or kilowatts)
  - The motion a force creates when exerted on an object over time
  - Typically, power is constant with speed variations for a piston engine
  - Thrust x Velocity

Positive Climb Performance: Aircraft gains PE by increasing altitude

- Aircraft uses excess power above what's required for level flight
- Aircraft coverts airspeed (KE) to altitude (PE)

Straight and Level

Lift = Weight & Thrust = Drag

Drag

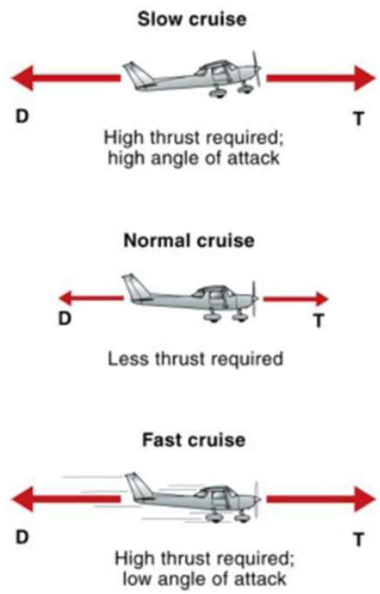
- Parasitic drag increases with airspeed
- Induced drag decreases with airspeed
- Power = Drag x Velocity

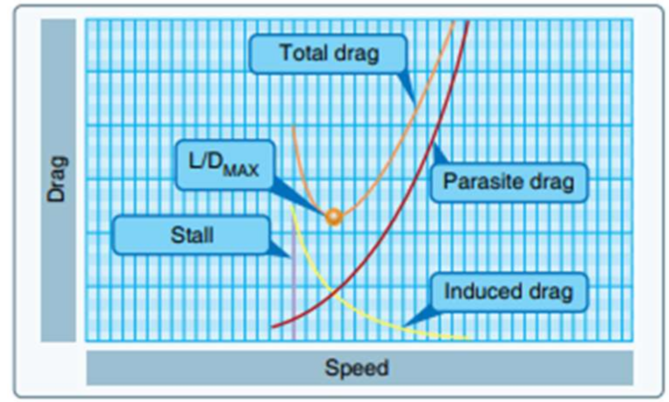
Max Level Flight Speed

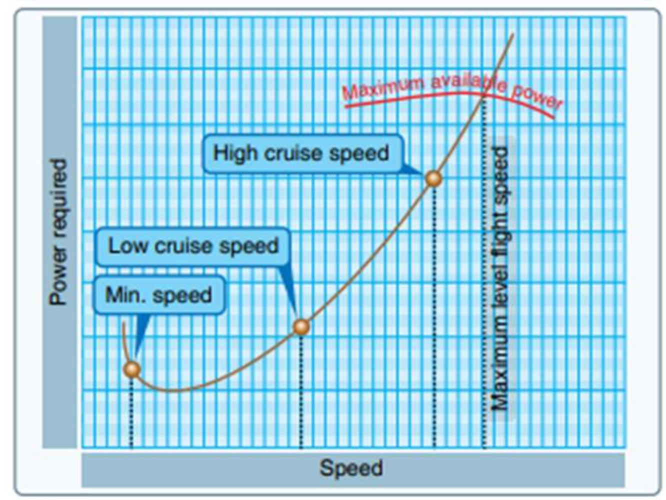
- When power required = power/thrust available

Min Level Flight Speed

- Not defined by thrust/power requirements
- Stall occurs first







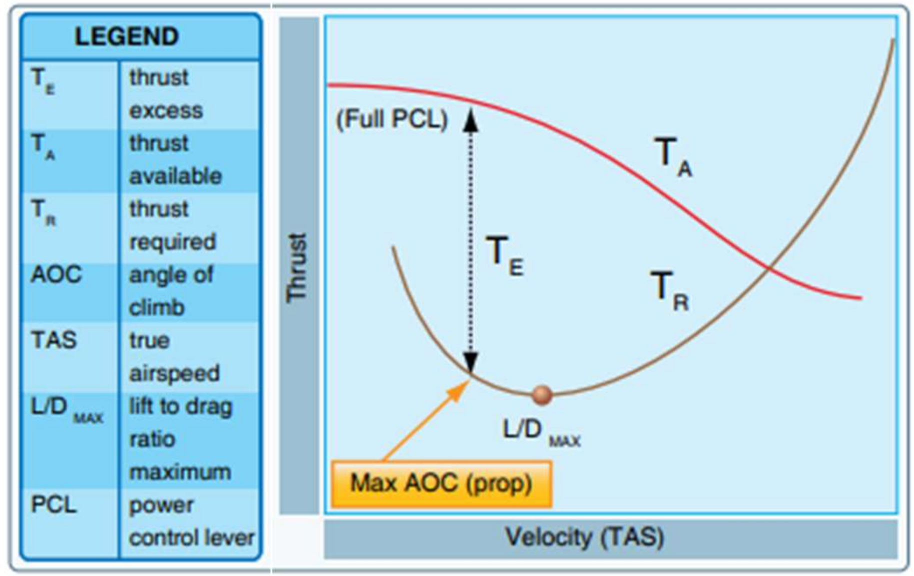
Angle of Climb

Comparison of altitude gained relative to distance traveled

- V_X is used for maximum AOC performance

Max AOC: Airspeed & AOA combination resulting in maximum excess *thrust*

- Propeller Plane: Below L/D_{MAX} and just above stall speed
- Warrior: V_x=63, V_S=50, V_{glide}=73
- Archer: V_x=64, V_S=50, V_{glide}=76
- Arrow: V_x=72, 78, V_S=60, V_{glide}=79



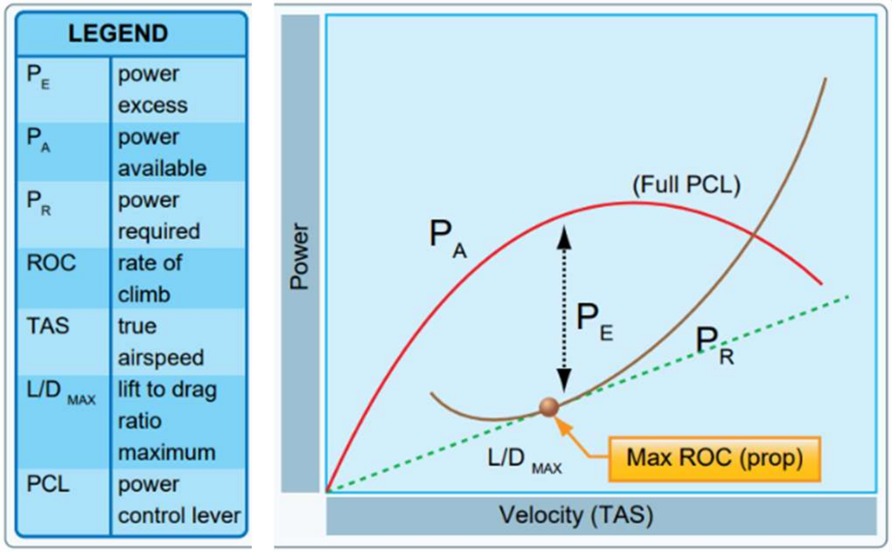
Rate of Climb

Comparison of altitude gained relative to the time needed to reach an altitude

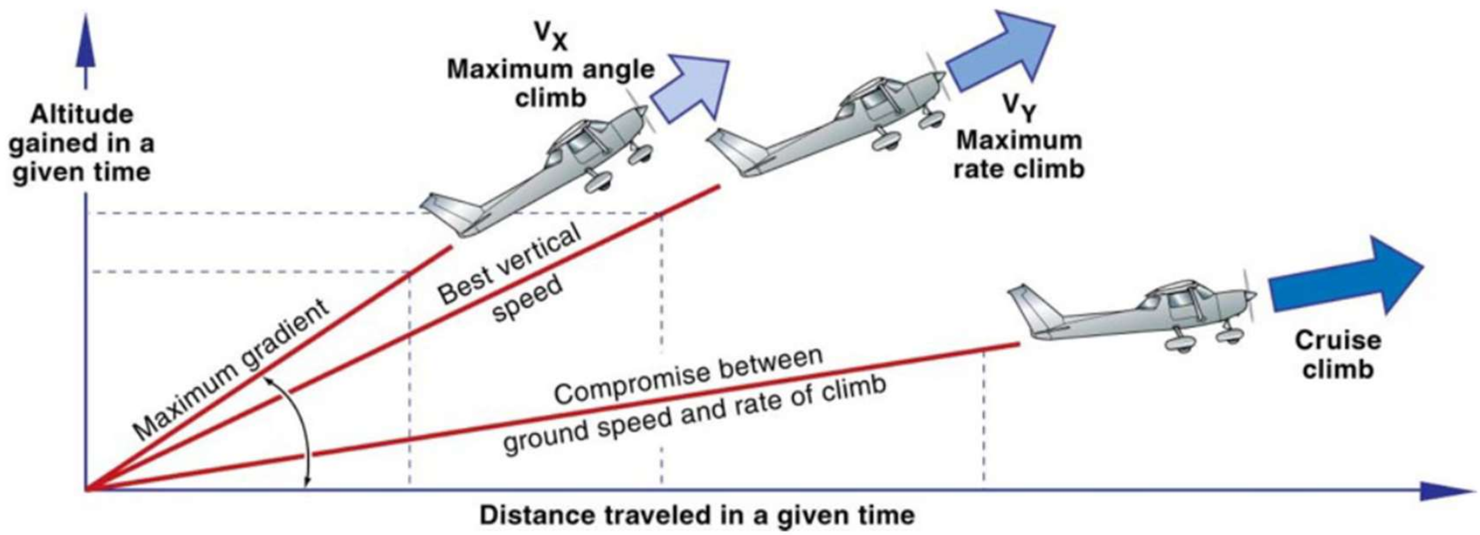
- V_Y is used for maximum ROC performance

Max ROC: Airspeed & AOA combination resulting in maximum excess *power*

- Propeller Plane: Maximum ROC speed, V_y, Close to L/D_{MAX}
- Warrior: V_y=79, V_{glide}=73
- Archer: V_y=76, V_{glide}=76
- Arrow: V_y=78, 90, V_{glide}=79



Types of Climbs



Climb Performance Factors

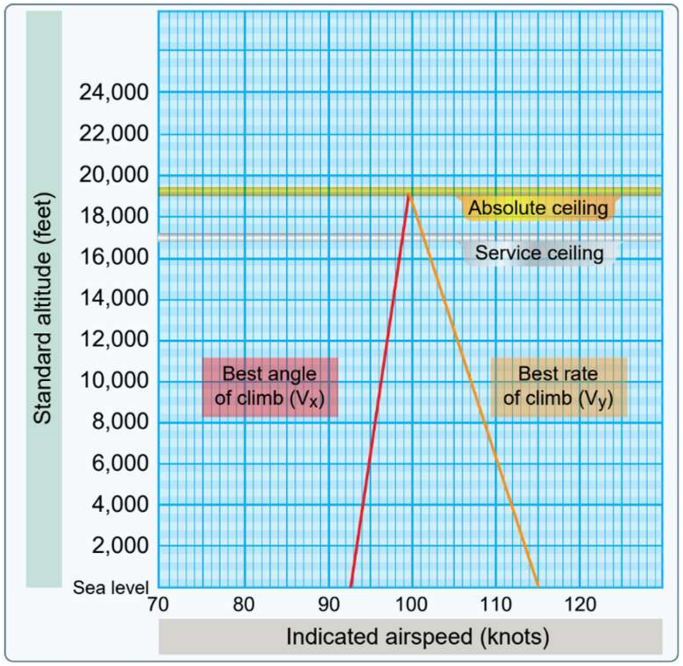
Increased weight & altitude, and lowering gear & flaps decreases excess thrust and power

Weight

- Added weight requires a higher AOA, increasing drag
- Increased drag requires additional thrust
- Added thrust means less reserve thrust to climb

Altitude

- Climb performance diminishes with altitude
- As altitude increases:
  - Max AOC, Max ROC, Min Level Flight Speed, & Max level Flight Speed all converge at the Absolute Ceiling
  - **Service Ceiling**: Maximum rate of climb is 100 fpm (feet per minute)
  - **Absolute Ceiling**: No excess power, only one airspeed allows level flight



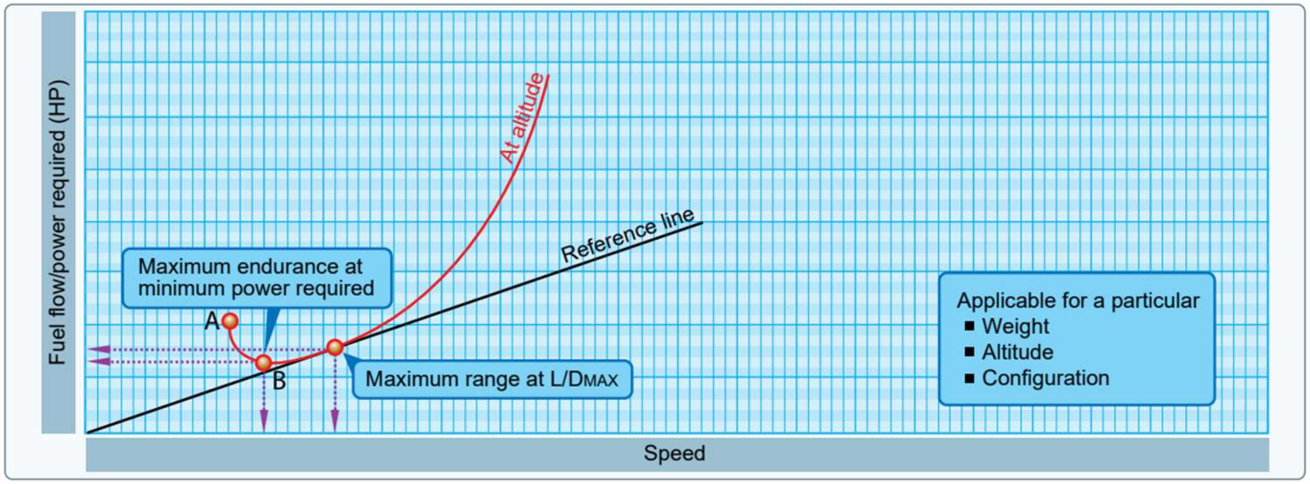
Range and Endurance

Maximum Range

- Distance an airplane can fly
- Best NM per pound of fuel
- Maximize L/D for piston engines

Maximum Endurance:

- Maximum time aloft
- Targets minimum fuel flow / minimum power required
- Slower than maximum range speed



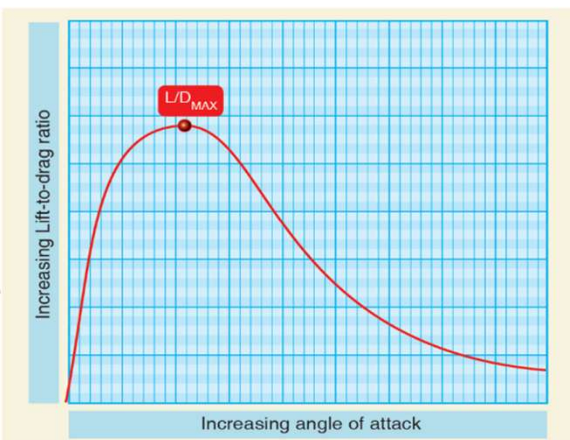
Best Glide Speed (no power available)

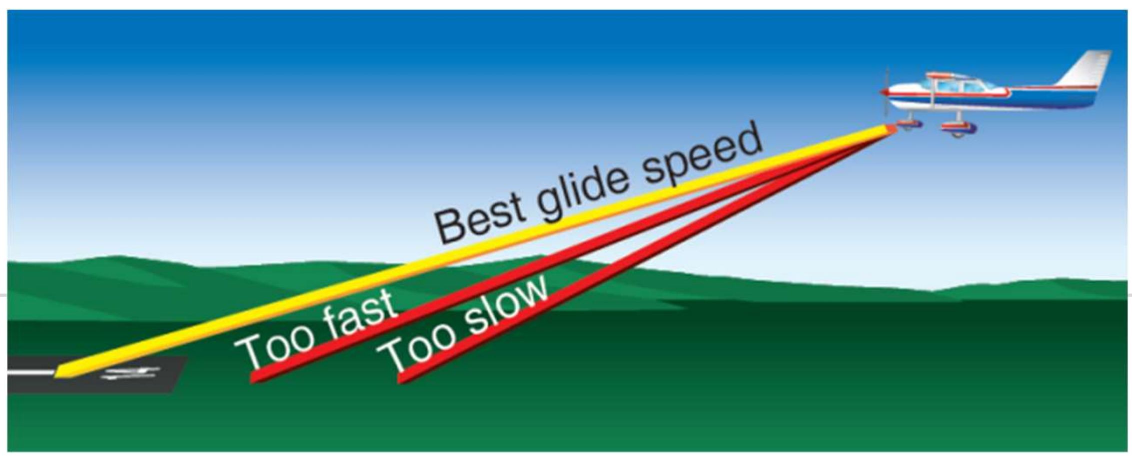
L/D determines the distance an airplane can glide, speed giving L/D_{MAX} determines glide range

Glide Ratio: Distance the airplane travels in relation to the altitude it loses

- Provides estimate of how far you can fly
- Any speed above or below Best Glide reduces the glide ratio

- **A heavier plane needs to fly at a higher speed to obtain the same L/D_{MAX}**
  - The heavier plane will travel the same distance as the lighter plane, but in a shorter time



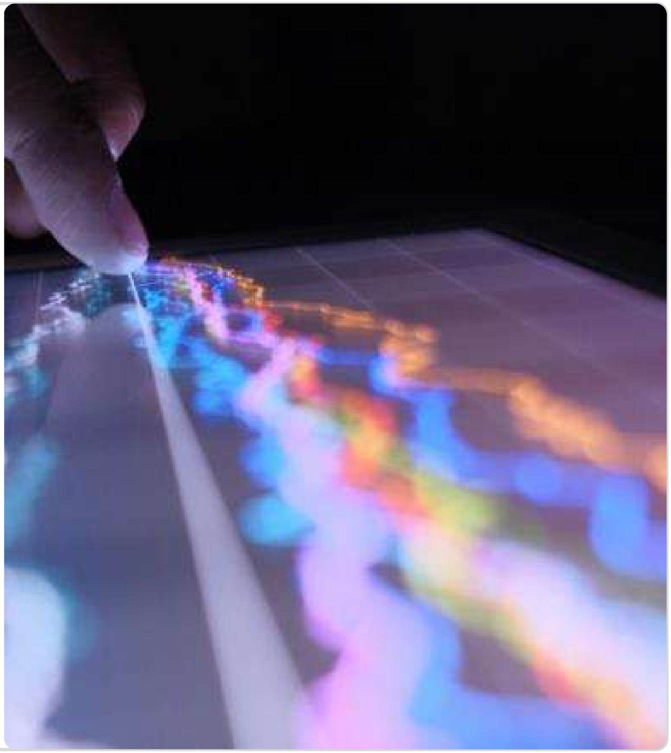


Performance Charts in the POH

POH Section 5 (Performance & Limitations)

Using the charts, we can calculate:

- Cruise Performance
- Stalls Speed based on configuration
- Wind Components
- Takeoff and Landing Distance
- Climb Performance
- True Airspeed
- Maximum Fight Duration
- *Charts available vary based on aircraft



Outline

- Fundamentals of aerodynamics
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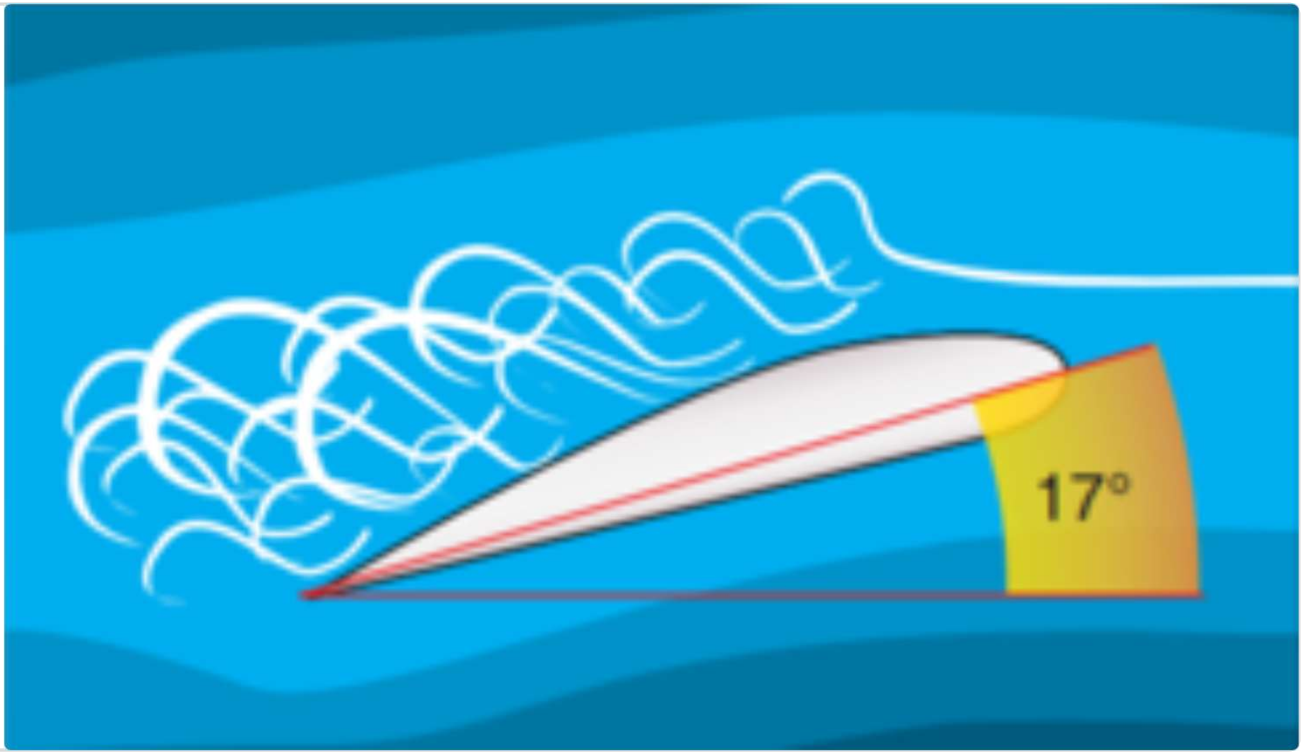
Introduction to Stalls

Direct cause of all stalls is an excessive angle of attack

- Stall speed varies
- Stall AOA is always the same (generally, 16-20 degrees)

Stall speed varies

Stall AOA is always the same (generally, 16-20 degrees)



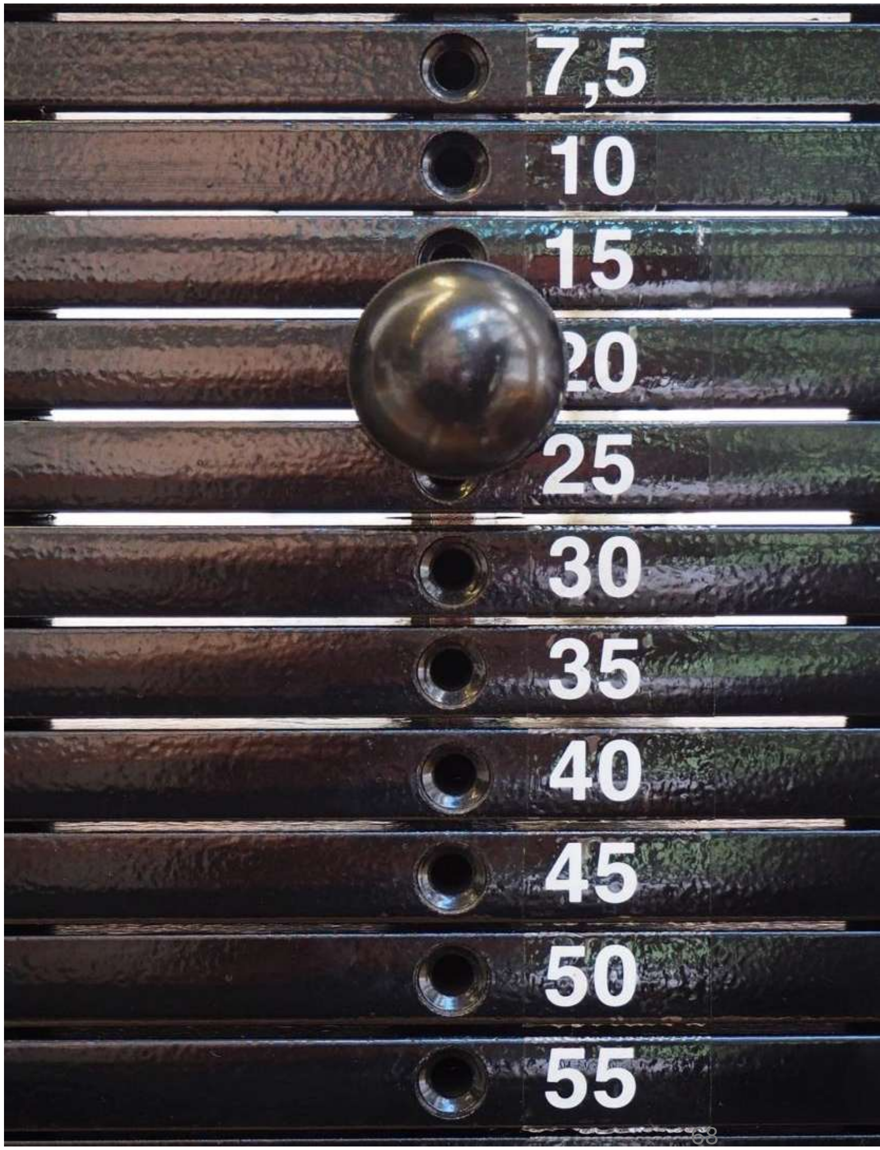
Weight and Stall Speed

Heavier aircraft require a higher AOA to maintain level flight

- Closer to the critical AOA than a lighter aircraft

A heavier aircraft is more stable

Increased weight & stability can assist in controlling the aircraft



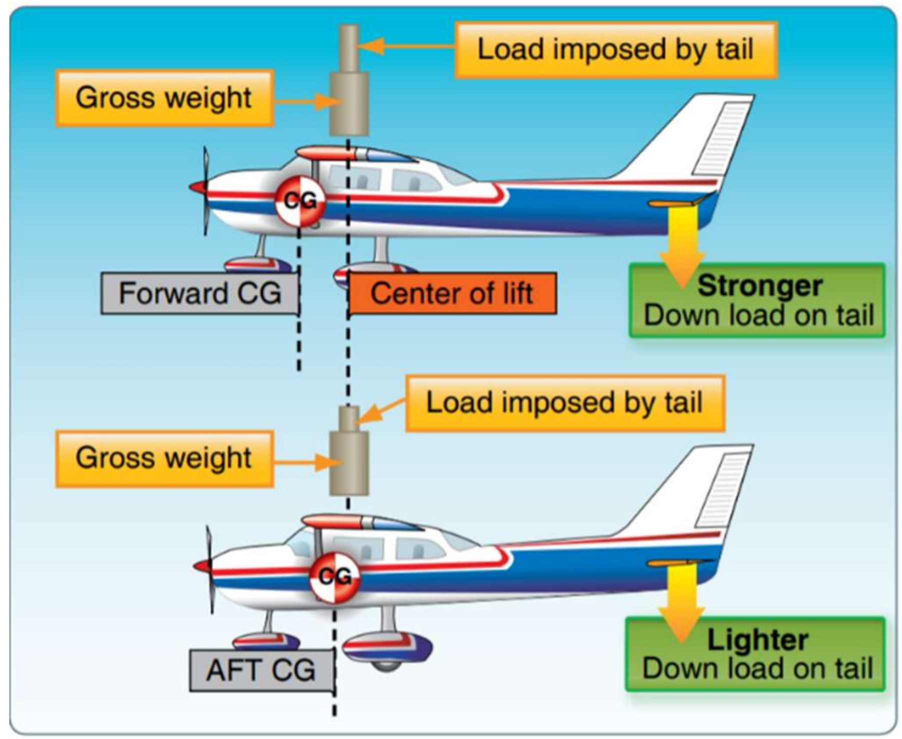
Center of Gravity and Stall Speed

Forward CG: Increases stall speed

- Same effect as a heavier aircraft
- More controllable, improving stall recovery
- Nose has a greater tendency to pitch down

Aft CG: Decreases stall speed

- Same effect as a lighter aircraft
- Less controllable, making stall recovery more difficult
- Nose has less of a tendency to pitch down



Stalls Occur in all Phases of Flight

A stall can occur in any phase of flight

Low Speed

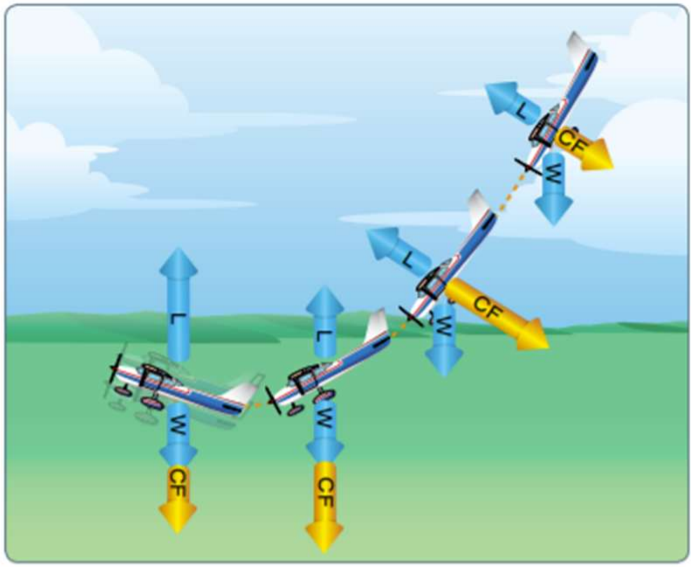
- As airspeed decreases, AOA must be increased to maintain altitude

High Speed

- High speed dive with a sudden increase in back pressure

Turning

- Stall speeds are higher in a level turn than in straight-and-level flight
- Wing must produce additional lift to counter the load imposed in a turn



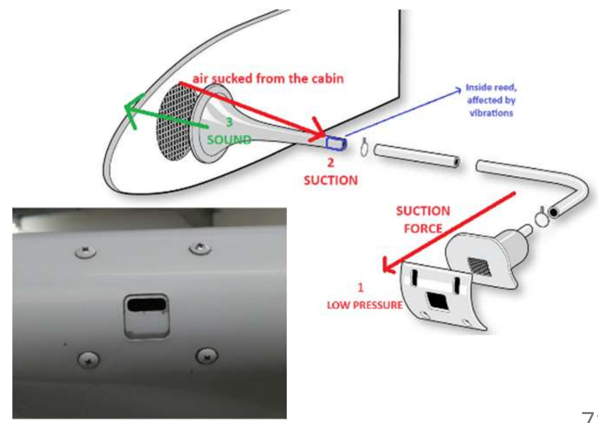
The critical angle of attack can be exceeded at any speed

Stall Warnings

- Warning horn: typically 5 kts before stall
- Warning light
- Buffet
- Nose drop

Piper Warrior (electric) Stall Horn

Cessna Stall Horn



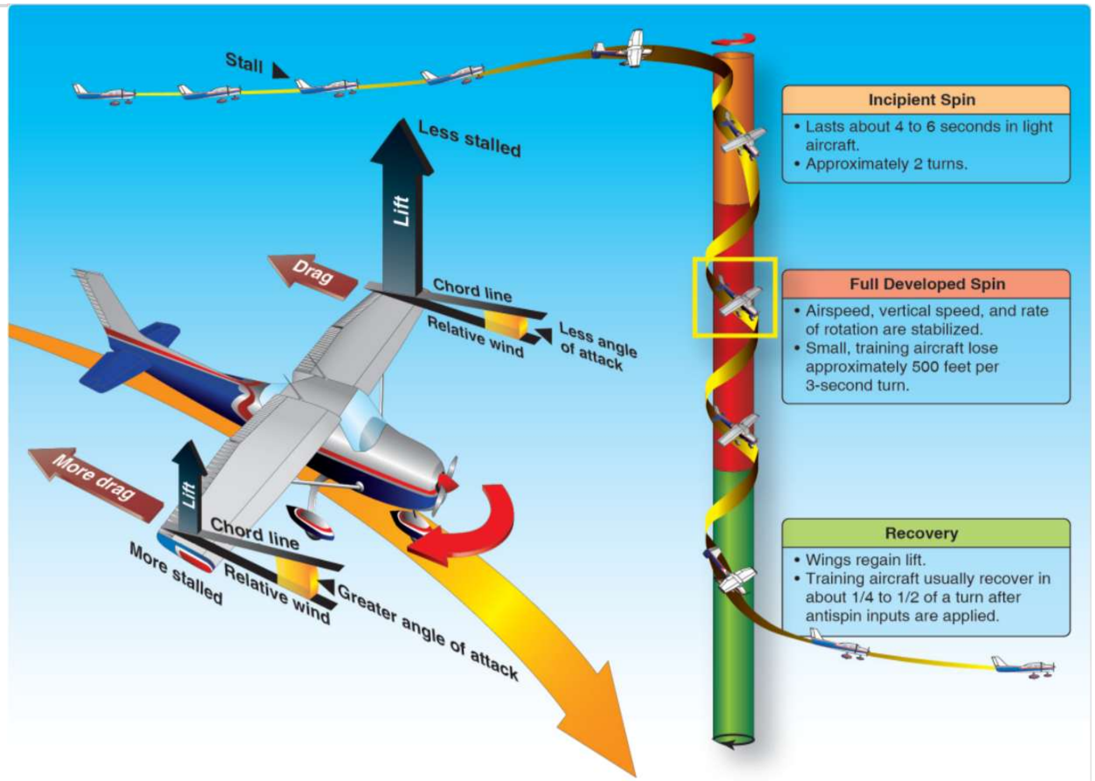
Stall Recovery

- Release back pressure (allow the nose to drop)
- Full power (increase airspeed)
- Maintain coordination

Recover at first indication for any unintentional stall

Basics of a Spin

- **Requirements for a spin: Stall + Rotation (yaw)**
- **Low wing is more stalled than the high wing creating an autorotation around the vertical axis**



Spin Aerodynamics

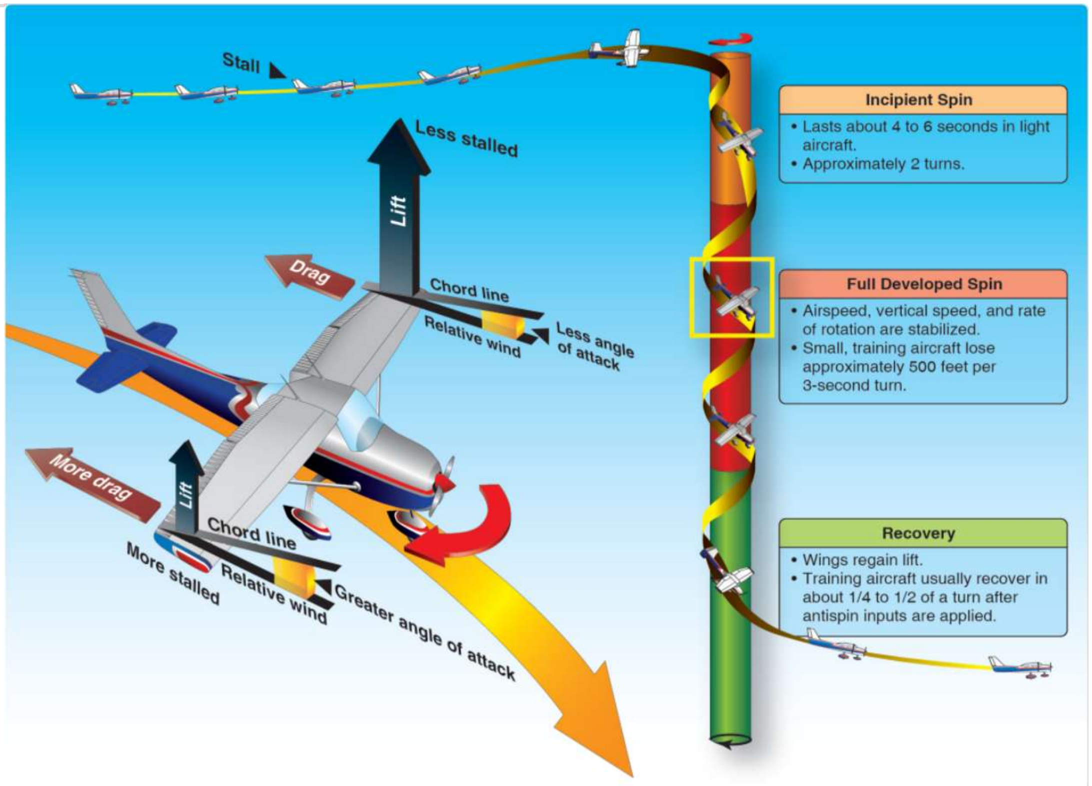
During the stall one wing drops

- Low wing has an increasing AOA
- High wing has a decreasing AOA

Autorotation is from unequal AOA

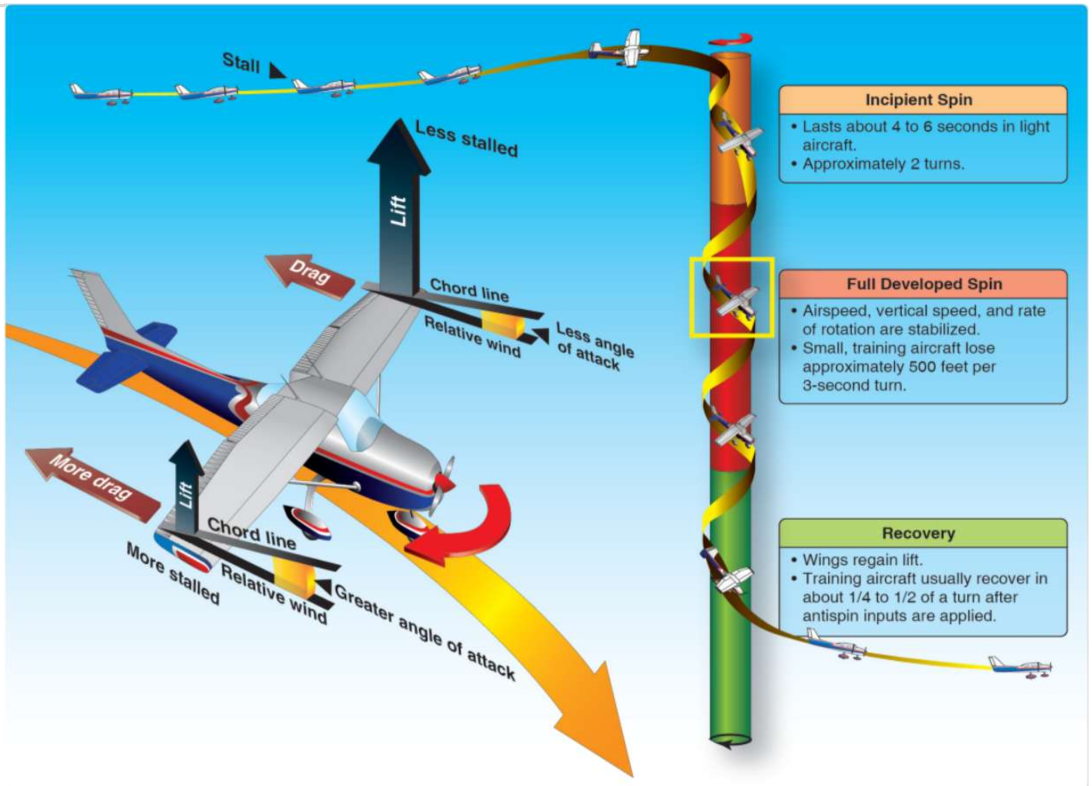
Load factor is slightly above 1G

- Airspeed is very low
- Aircraft pivots, rather than turns, while in a spin



Phases of a Spin

1. **Stall / Entry**
2. **Incipient**
3. **Developed**
4. **Recovery**



Cessna 152 Spin Video

Spin Recovery: Memorize PARE

- **P**ower: Idle
- **A**ilerons: neutral
- **R**udder: opposite the spin
    - Look at the ground rotation
    - Rate of turn indicator
        - Attitude indicator will exceed limits and be erroneous
        - Ball indicates which side of the plane its on
- **E**levator: forward then slowly raise after rotation stops

Questions?