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Private Pilot Ground School
Massachusetts Institute of Technology
IAP 2019

Airplane Aerodynamics

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AIRPLANE PARTS

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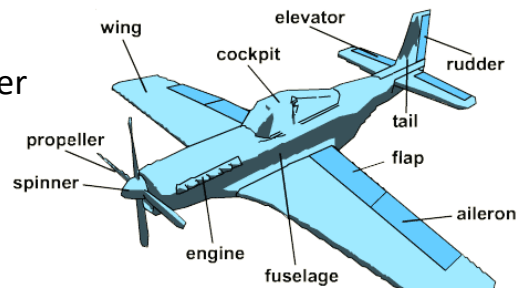
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Major Airplane Parts

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- Engine & Propeller
- Fuselage
- Empennage
 - Vertical Stabilizer
 - Horizontal Stabilizer
- Wing
 - Strut
- Landing Gear



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AERODYNAMIC PRINCIPLES: FOUR FORCES OF FLIGHT

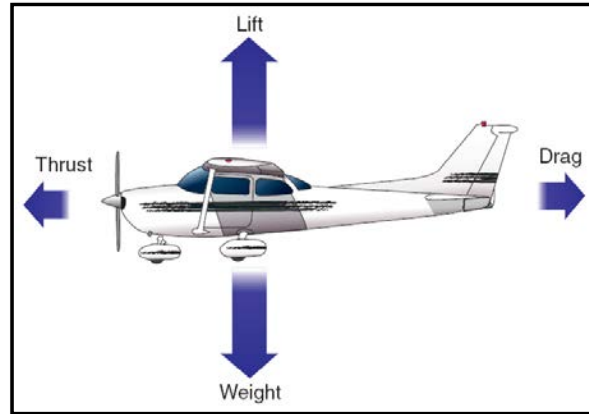
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Four Forces of Flight

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- Lift
- Weight
- Thrust
- Drag



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Lift

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- [black board]

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Lift

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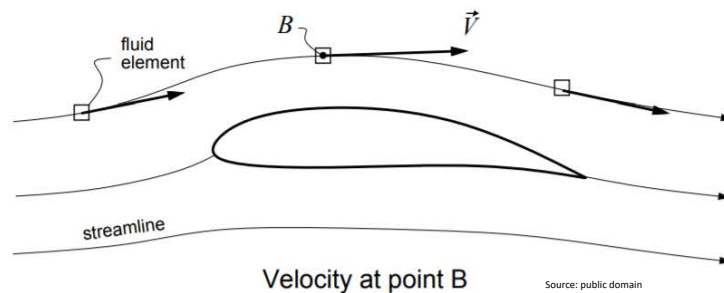
- A mathematical description is not necessary in order to pilot an airplane. We will describe the basic ways lift is generated, but more importantly how you will control it as a pilot.
- Consult the FAA *Pilot's Handbook of Aeronautical Knowledge*
 - Also good: [Understanding Flight](#) by David F. Anderson and Scott Eberhardt

Note that most lay explanations of lift are wrong!

Lift

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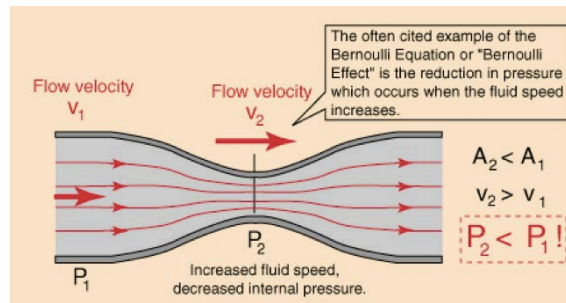
- For lift, must increase downward momentum of the air
- Airfoils can increase downward momentum efficiently



Bernoulli's Principle

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- Relates pressure and velocity of fluid
 - Increase in velocity
 - Decrease in pressure



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Practice Question

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- Which statement relates to Bernoulli's principle?
- For every action there is an equal and opposite reaction
 - An additional upward force is generated as the lower surface of the wing deflects air downward
 - Air traveling faster over the curved upper surface of an airfoil causes lower pressure on the top surface

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Practice Question

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Which statement relates to Bernoulli's principle?

- A. For every action there is an equal and opposite reaction
- B. An additional upward force is generated as the lower surface of the wing deflects air downward
- C. Air traveling faster over the curved upper surface of an airfoil causes lower pressure on the top surface**

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Lift

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- [black board]

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Lift

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- What part of the aircraft generates lift?

Lift

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Lift is a Force: Basic Physics (not on FAA test)

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- Simply put:
 - $F = ma$
 - Or: $F = \frac{\Delta(mv)}{\Delta t}$
 - Force is rate of change of momentum
- To get lift, we need to impart a change in momentum on the aircraft, and thus on the air (Newton's third law)

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Lift

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- Which moves faster,
the aircraft through the air
or the air past the aircraft?

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Factors affecting Lift

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- Object
- Motion
- Air

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Calculating Lift

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- Calculating lift is difficult.
- We've gotten better at approximating it:

- 5 Mathematical theories of lift
 - 5.1 Navier-Stokes (NS) equations
 - 5.2 Reynolds-Averaged Navier-Stokes (RANS) equations
 - 5.3 Inviscid-flow equations (Euler or potential)
 - 5.4 Linearized potential flow
 - 5.5 Circulation and Kutta-Joukowski
 - 5.6 Lift coefficient
 - 5.7 Pressure integration
 - 5.8 Control volumes
- 6 Three-dimensional flow
 - 6.1 Wing tips and spanwise distribution
 - 6.2 Horseshoe vortex system
- 7 Alternative explanations, misconceptions, and controversies
 - 7.1 False explanation based on equal transit-time
 - 7.2 Controversy regarding the Coandă effect

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Ref: [https://en.wikipedia.org/wiki/Lift_\(force\)#Mathematical_theories_of_lift](https://en.wikipedia.org/wiki/Lift_(force)#Mathematical_theories_of_lift) Private Pilot Ground School

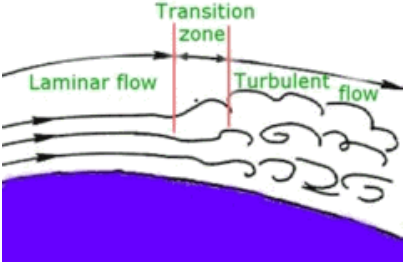
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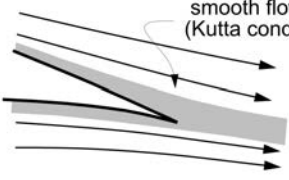
Limitations

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smooth flow-off
(Kutta condition)

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Ref: http://www.formula1-dictionary.net/boundary_layer.html



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Approximating Lift (1)

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- If you know the pressure distribution on the airfoil surface, and make some assumptions:

$$L = \oint p \mathbf{n} \cdot \mathbf{k} \, dS$$

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Approximating Lift (2)

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- Calculate what you can, measure the rest:

$$L = \frac{1}{2} \rho v^2 AC_L$$

 Coefficient of Lift is measured at a given angle of attack

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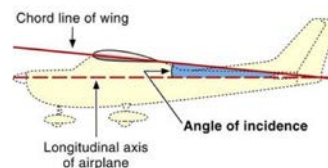
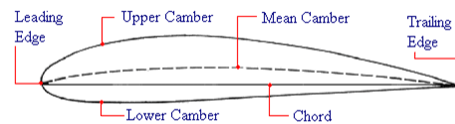
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The Airfoil

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- Leading Edge
- Trailing Edge
- Camber
- Chord
- Angle of Attack
- Angle of Incidence
- Center of Pressure



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How can we control lift?

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1. Camber – Wing design
2. Wing Area – Wing design, or modified from the cockpit with flaps
3. Airspeed
4. Angle of Attack
5. Flaps (changes effective camber), spoilers

For steady, level flight: $Lift = Weight$

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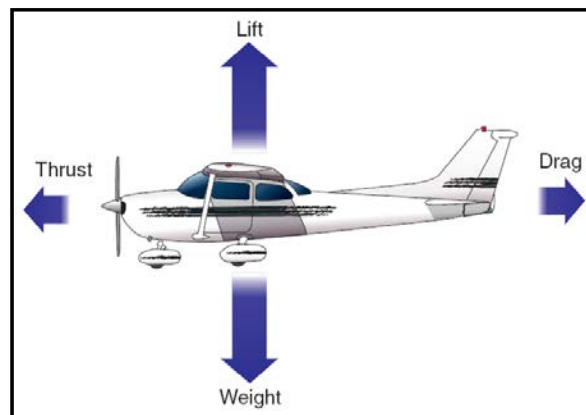
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Four Forces of Flight

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- Lift
- Weight
- Thrust
- Drag



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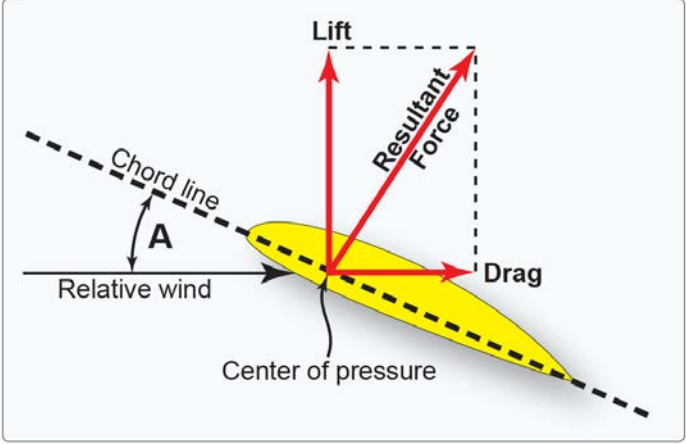
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Angle of Attack

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Lift

Resultant Force

Chord line

A

Relative wind

Drag


Center of pressure

FIGURE 1.—Lift Vector.

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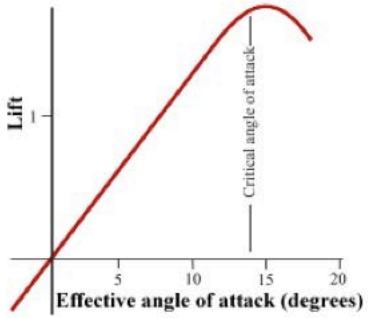
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Angle of Attack

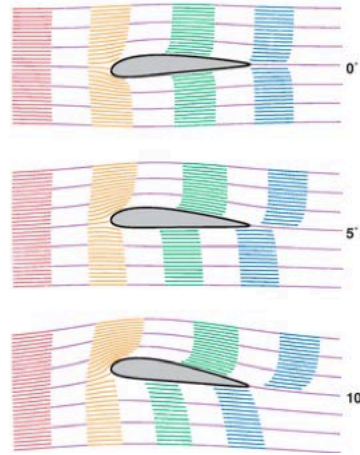
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Lift

Effective angle of attack (degrees)

Critical angle of attack



0°

5°

10°

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Source: public domain

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Practice Question

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The term “angle of attack” is define as the angle between the:

- A. Chord line of the wing and the relative wind
- B. Airplane’s longitudinal axis and that of the air striking the airfoil
- C. Airplane’s centerline and the relative wing

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Practice Question

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The term “angle of attack” is define as the angle between the:

- A. Chord line of the wing and the relative wind**
- B. Airplane’s longitudinal axis and that of the air striking the airfoil
- C. Airplane’s centerline and the relative wing

Also, the angle of attack for a propeller is defined as the angle between the propeller chord line and the relative wind.

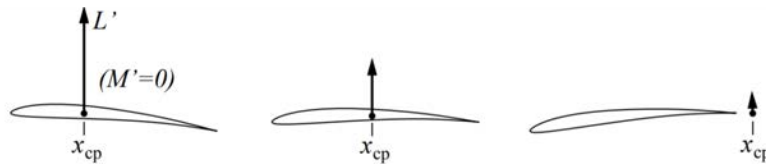
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Center of Pressure

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- Point on wing chord where the lift force is centered
 - May change as angle of attack increases and decreases
- Location of the Center of Pressure affects aerodynamic balance and controllability



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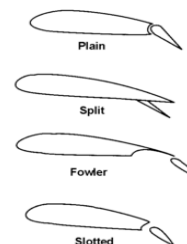
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Flaps

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- Flaps increase lift-producing capability of the wing
- Flaps increase total drag
- Full flaps increase the approach-to-landing angle without increasing airspeed
- Partial flaps may be useful or required for taking off



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Thrust

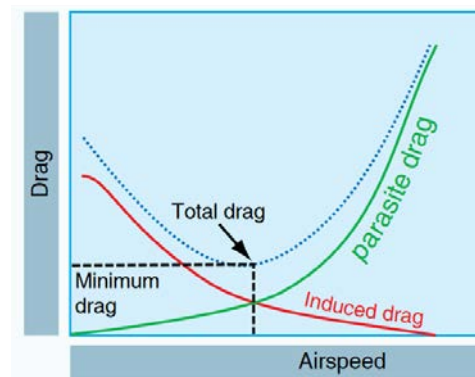
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- Propeller = rotating wing
- Thrust is produced by a propeller in same way that lift is produced by a wing
- Usually, when discussing propeller driven aircraft, we use power (in HP) instead of thrust (in pounds)

Drag

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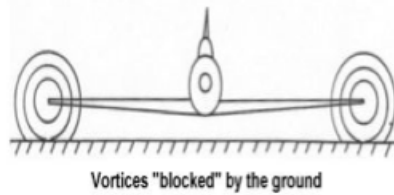
- Parasitic Drag
 - Produced by aircraft as it moves through air
 - Increases with square of airspeed
- Induced Drag
 - Drag created by lift
 - Increases at high Angle of Attack/Lower Airspeed
 - Highest at slow speed in landing configuration
- See: PHAK: 5-6



Ground Effect

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- Within one wingspan of the ground
 - Induced drag decreases
 - Aircraft may become airborne at lower speed than it can sustain flight
 - Plane may float much longer on landing



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AERODYNAMIC PRINCIPLES: STABILITY

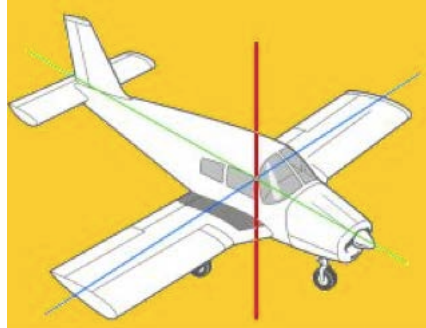
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Three Axes of Flight

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- Longitudinal (green)
 - Nose to tail
- Lateral (blue)
 - Wingtip to wingtip
- Vertical (red)
 - Top to bottom



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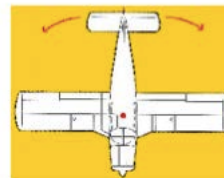
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The Flight Controls

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- **Elevator** to control **Pitch**
 - Motion about the lateral axis
- **Ailerons** to control **Roll**
 - Motion about the longitudinal axis
- **Rudder** to control **Yaw**
 - Motion about the vertical axis



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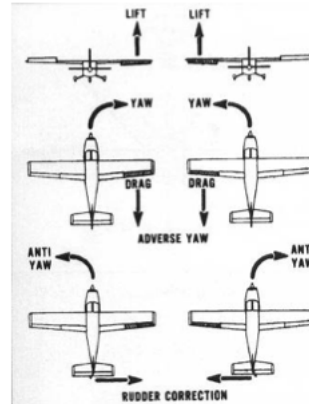
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Adverse Yaw (Or why we have a rudder)

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



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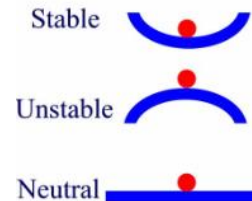
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Static Stability

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- 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



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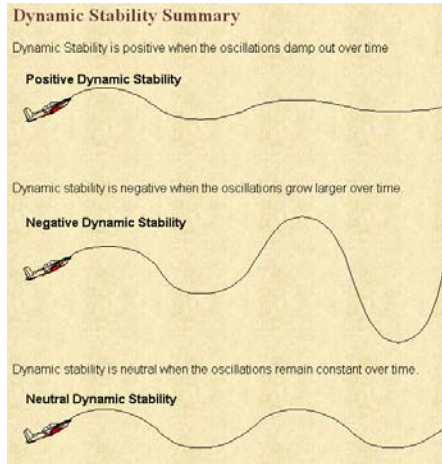
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Dynamic Stability

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- Positive
 - Oscillations decrease in amplitude with time
- Neutral
 - Oscillations are constant in amplitude with time
- Negative
 - Oscillations increase in amplitude with time
- Above are all types of Positive Static Stability



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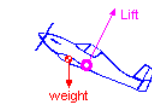
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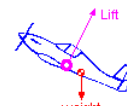
Longitudinal Stability

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- Stability about lateral axis (“pitch axis”)
- Dependent on location of Center of Gravity
 - CG forward \rightarrow Stable
 - CG aft \rightarrow Unstable
 - Stall recovery may be difficult



When the CG is ahead of NP the weight tends to correct the upset = Stable



When the CG is behind NP the weight worsens the upset = Unstable

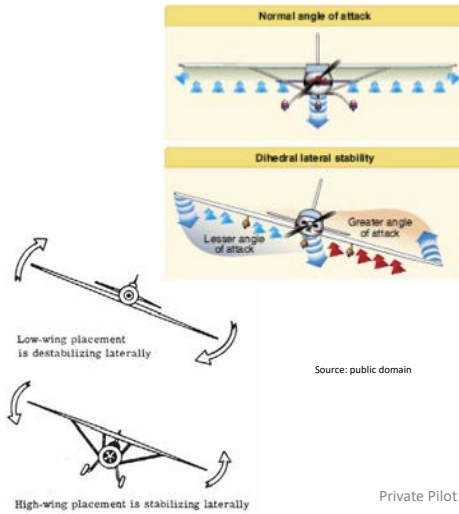
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Lateral Stability

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- Stability about longitudinal axis
 - Roll Stability
- Can be influenced by
 - Dihedral (wings angled upward when viewed from the front)
 - Sweepback (wings canted backward when viewed from above)
 - High vs. Low Wing

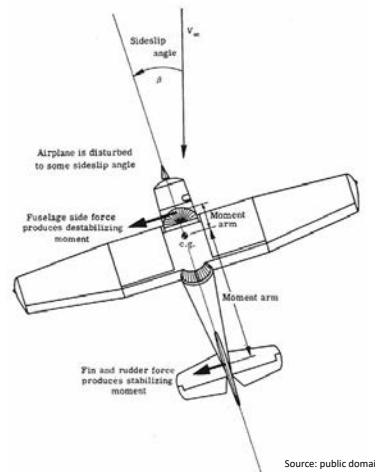
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Directional Stability

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- Stability about vertical axis
- Influenced by location of vertical stabilizer
 - Similar to weather vane or feathers on an arrow



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Stall

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- At a certain angle of attack, airflow cannot “stick” to top of the wing
- Air flow separation occurs
- Stalls can occur at any airspeed



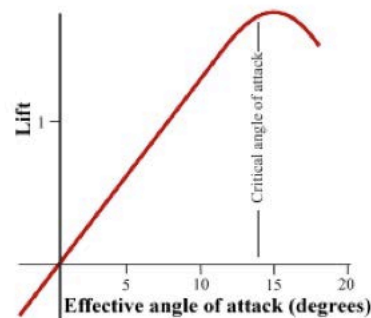
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Stall

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- The “critical angle of attack” does not change for a given wing
- Large loss of lift when stalled



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Spins

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- Uncoordinated stalls result in spins
- Both wings are stalled, one more stalled than other
- Rotating helical downward path
- Hazardous near the ground, in aircraft not rated for spins, or in all aircraft when not intentional
- Demonstration not required for PPL training or test, but knowledge is important

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AERODYNAMICS OF MANEUVERING FLIGHT

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Climbing Flight

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- Airplane begins to climb when lift temporarily exceeds weight
- In a steady climb, the four forces are still in equilibrium
- Rate at which airplane climbs determined by excess thrust

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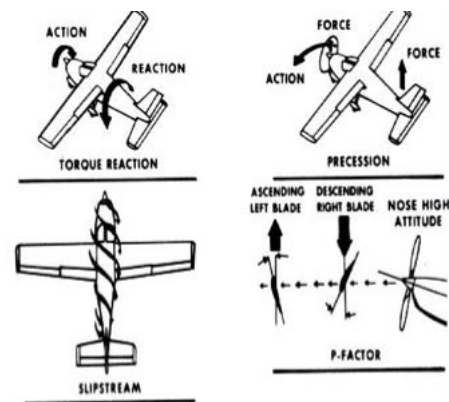
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Left Turning Tendencies

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- Torque
- P Factor
- Spiraling Slip Stream
- Gyroscopic Precession
 - This is not always a left turning tendency



https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/07_phak_ch5.pdf

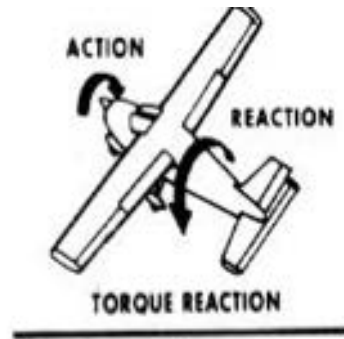
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Left Turning Tendencies

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- Torque
 - For every action, there is an equal and opposite reaction
 - Most US aircraft engines rotate the propeller clockwise, as viewed from pilot's seat
 - The aircraft tends to roll left



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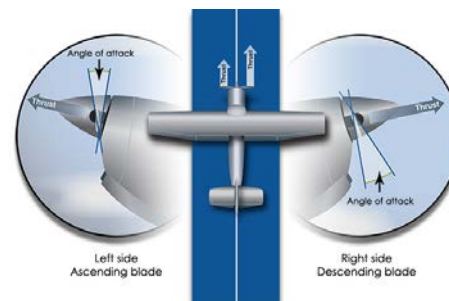
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Left Turning Tendencies

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- P-Factor/Asymmetrical Thrust
 - When airplane has a high angle of attack (climb or slow flight), the descending right propeller blade creates more thrust than the ascending left blade
 - The center of thrust moves to the right
 - Difference in thrust creates left yaw



Source: public domain

<https://aviation.stackexchange.com/questions/312/whats-p-factor-and-why-does-it-occur>

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Left Turning Tendencies

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- Spiraling Slip Stream/
Corkscrew Effect
 - High speed rotation of propeller
 - Air pulled in by the propeller is rotated and sent backward, moving in a clockwise corkscrew pattern around the fuselage
 - Air hitting vertical stabilizer causes left yaw

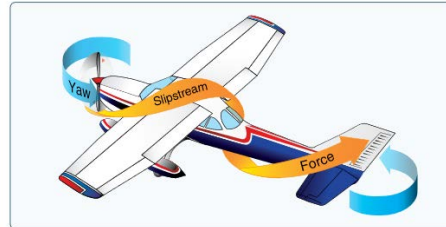


Figure 5-48. Corkscrewing slipstream. Source: public domain

https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/07_phak_ch5.pdf

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Practice Question

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The left turning tendency of an airplane caused by P-factor is the result of the

- A. Propeller blade descending on the right producing more thrust than the ascending blade on the left.
- B. Clockwise rotation of the engine and the propeller turning the airplane counter-clockwise This is because of torque.
- C. Gyroscopic forces applied to the rotating propeller blades acting 90 degrees in the advance of the point the force was applied

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Practice Question

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The left turning tendency of an airplane caused by P-factor is the result of the

- A. Propeller blade descending on the right producing more thrust than the ascending blade on the left.
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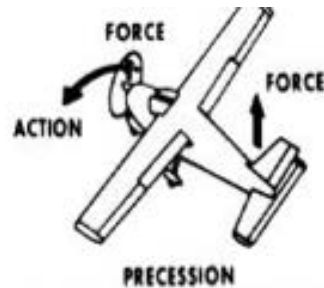
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Left Turning Tendencies

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- Gyroscopic Precession
 - Gyroscopes:
 - Rigidity in space
 - Precession
- Precession is the resultant action of a spinning rotor when a deflecting force is applied.
- Any time a force is applied to deflect the propeller out of its plane of rotation, the resulting force is 90° ahead of and in the direction of rotation and in the direction of application, causing a pitching moment, a yawing moment, or a combination.



Source: public domain

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https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/07_phak_ch5.pdf



Descending Flight

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- Airplane descends when flight path is pointed downward
- 4 forces are still in equilibrium

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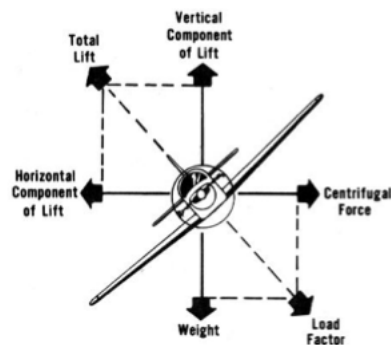
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Turning Flight

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- Horizontal component of lift turns plane
- Rudder is used to maintain coordination
- 4 forces are not in equilibrium, this is accelerated flight



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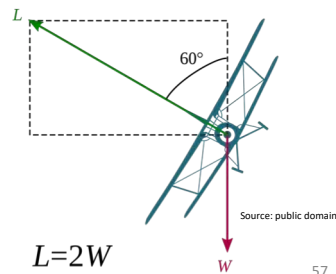
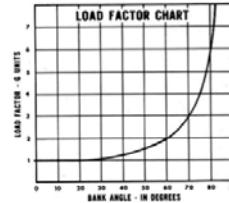
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Load Factor

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- Weight of Aircraft divided by weight supported by wings (lift)
- Often referred to as “G’s”
- A load factor of 2, or “2 Gs”, means wings support 2x normal aircraft weight
- Increasing load factor increases stall speed



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AERODYNAMICS: DIFFERENT AIRCRAFT CONFIGURATIONS

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Blended Wing Body

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<http://www.dailymail.co.uk/sciencetech/article-3785673/Is-future-flying-Boeing-tests-blended-wing-plane-skies-10-years.html>


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What you learned

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- How an airplane generates lift
- Factors that affect lift
- That lift is hard to calculate
- Forces on an airplane
- Stability
- Tendencies
- Different aircraft configurations


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Questions?

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Practice Question

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Wingtip vortices are created only when an aircraft is?

- A. Operating at high airspeeds
- B. Heavily loaded
- C. Developing lift

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Practice Question

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Wingtip vortices are created only when an aircraft is?

- A. Operating at high airspeeds
- B. Heavily loaded
- C. Developing lift**

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Practice Question

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How does the wake turbulence vortex circulate around each wingtip?

- A. Inward, upward, and around each tip
- B. Inward, upward, and counterclockwise
- C. Outward, upward, and around each tip

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Practice Question

16.687

How does the wake turbulence vortex circulate around each wingtip?

- A. Inward, upward, and around each tip
- B. Inward, upward, and counterclockwise
- C. Outward, upward, and around each tip**

Wingtip vortices occur only when the aircraft is developing lift. Because of the lower pressure above the wing and higher pressure below the wing, the vortices circulate outward, upward, and around each wingtip.

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Thought Question

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Why do we care about wing tip vortices?

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Practice Question

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When departing behind a heavy aircraft, the pilot should avoid wake turbulence by maneuvering the aircraft

- A. Below and downwind from heavy aircraft
- B. Above and upwind from the heavy aircraft
- C. Below and upwind from the heavy aircraft

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Practice Question

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When departing behind a heavy aircraft, the pilot should avoid wake turbulence by maneuvering the aircraft

- A. Below and downwind from heavy aircraft
- B. Above and upwind from the heavy aircraft**
- C. Below and upwind from the heavy aircraft

Wingtip vortices sink below the aircraft generating them. Avoid wake turbulence by staying **above** and **upwind** of the generating aircraft's flightpath.

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Back-up


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Canards

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For more on canards, read this online textbook:
<http://docs.desktop.aero/appliedaero/configuration/canards.html>

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<https://vipcozy540.weebly.com/> Private Pilot Ground School 70



Back-up on Canards

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- Why was the Rutan Voyager a canard?
https://en.wikipedia.org/wiki/Rutan_Voyager
- It is possible to build 4-seat canards, e.g., https://en.wikipedia.org/wiki/Cozy_MK_IV ; if this is more efficient than a C172, why isn't it the dominant design for a family airplane?
- Why did the bizjet-sized true canard completely fail?
<https://airfactsjournal.com/2018/01/why-the-starship-was-such-a-disaster/>
- What about a three-surface airplane, such as https://en.wikipedia.org/wiki/Piaggio_P.180_Avanti ?
- Why does adding a canard to a conventional C182 enable it to land in less runway? (see <https://www.avweb.com/news/features/King-Katmai-Mod-Safe-STOL-224865-1.html>)

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Landing Sideways: Another good reason to have a rudder

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- Fly straight south to Florida with a wind from the west? No need for a rudder. Just turn to a slightly west heading.
- Land on a straight south runway with a wind from the west? Now you need a rudder! (or special sideways landing gear)



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