SPC 307

Introduction to Aerodynamics

# Lecture 3

February 12, 2016

# Chapter Summary

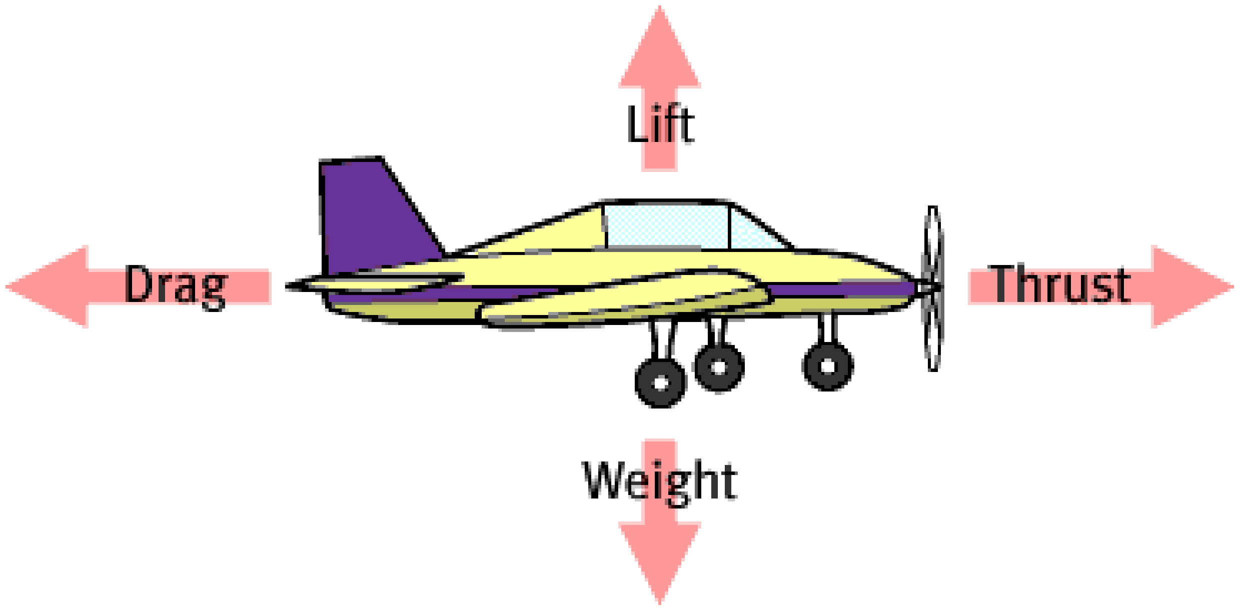
- Learn why aerodynamics is important in determining the performance characteristics of airplanes
- Develop a basic understanding of fluid properties such as density, temperature, pressure, and viscosity and know how to calculate these properties for a perfect gas
- Learn about the atmosphere and why we use a “standard atmosphere” model to perform aerodynamic calculations; learn how to perform calculations of fluid properties in the atmosphere
- Learn the basic components of an airplane and what they are used for.

# Incompressible flows around wings of finite span

- Understand the difference between airfoils and wings and know the physical processes that cause those differences
- Be able to describe the impact of wing-tip vortices on the flow around the airfoil sections that make up a wing
- Understand the concepts behind Lifting-Line theory and be able to use the results to predict the lift and induced drag of a wing
- Understand the basic approach and usefulness of panel methods and vortex lattice methods
- Understand how delta wing aerodynamics differ from traditional wing aerodynamics, and be able to compute the aerodynamic forces acting on a delta wing
- Be able to explain why some tactical aircraft use leading-edge extensions (strakes) and how they work
- Describe the asymmetric flow patterns that can take place around an aircraft flying at high angles of attack, and know the physical processes that cause the flow

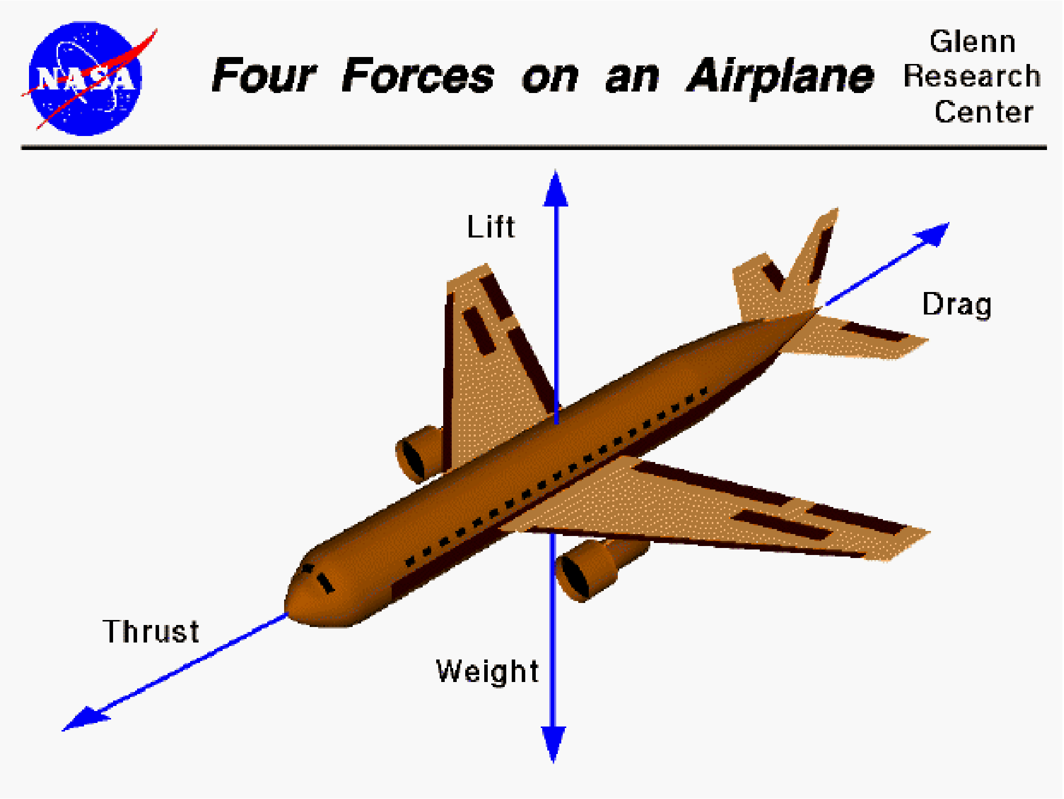
- The ability of an airplane to perform (how high, how fast, and how far an airplane will fly, such as the F-15E shown in Fig) is determined largely by the aerodynamics of the vehicle.

# The Four Forces of Flight




The four forces act on the airplane in flight and also work against each other.

# The Four Forces of Flight




The four forces act on the airplane in flight and also work against each other.

# What is Weight?

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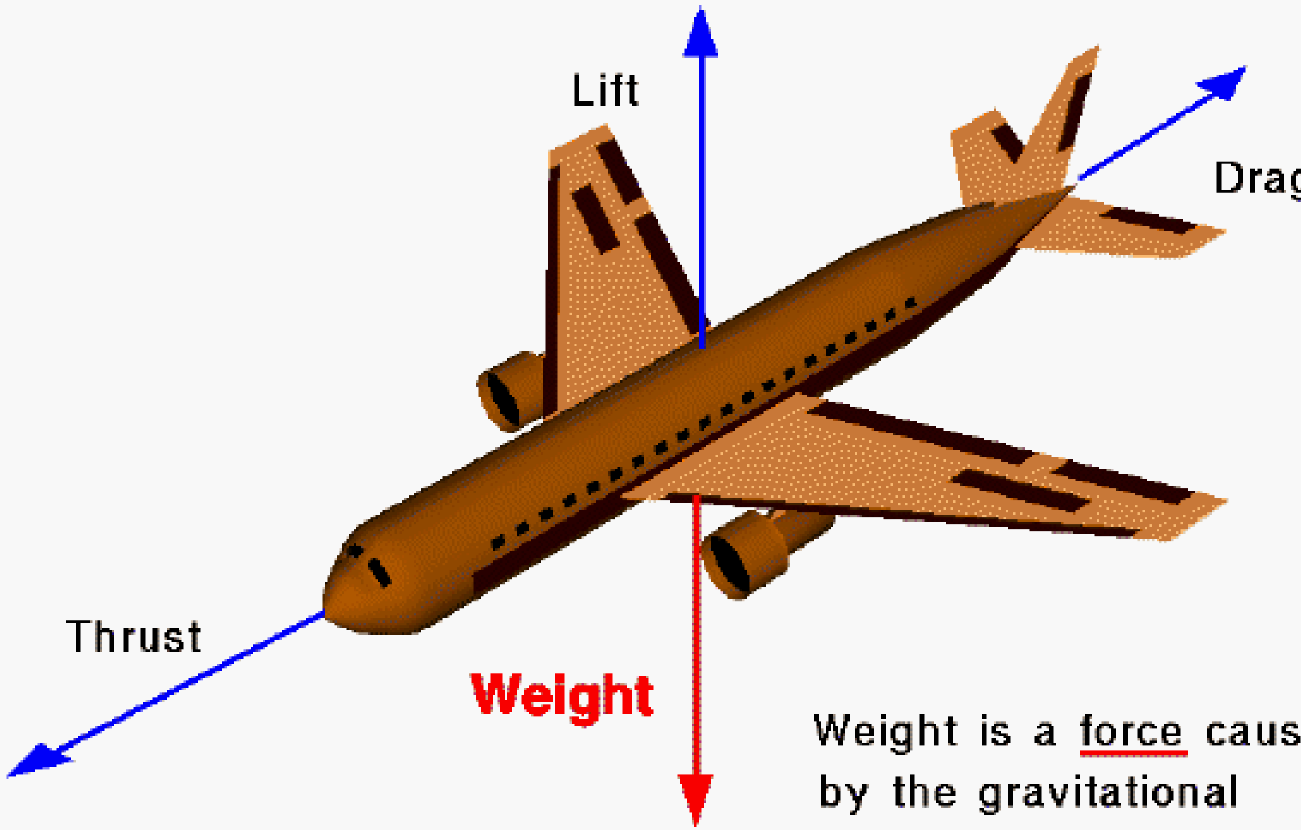
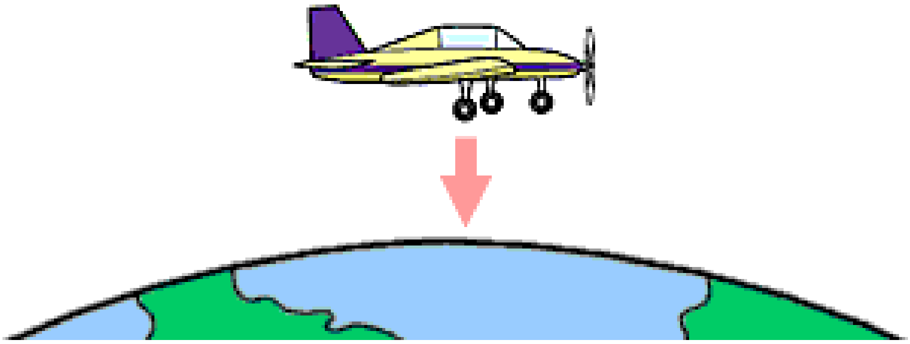
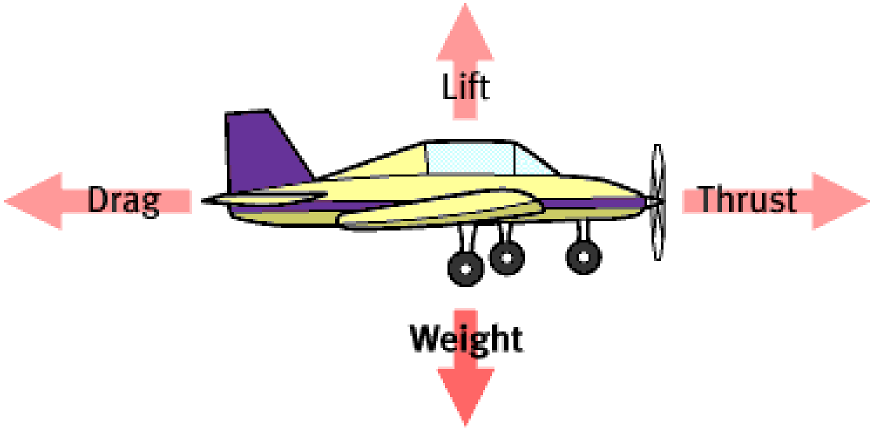



Weight is a force caused by the gravitational attraction of the Earth.

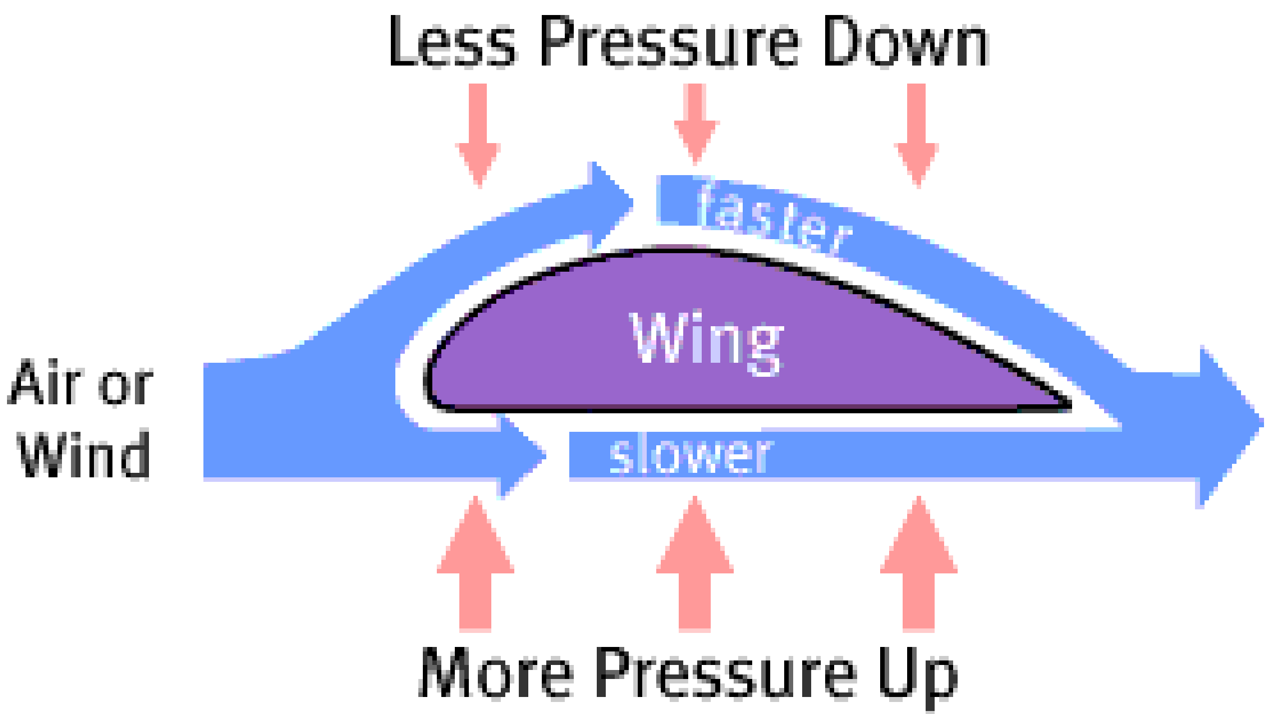
The earth's gravity pulls down on objects and gives them weight.



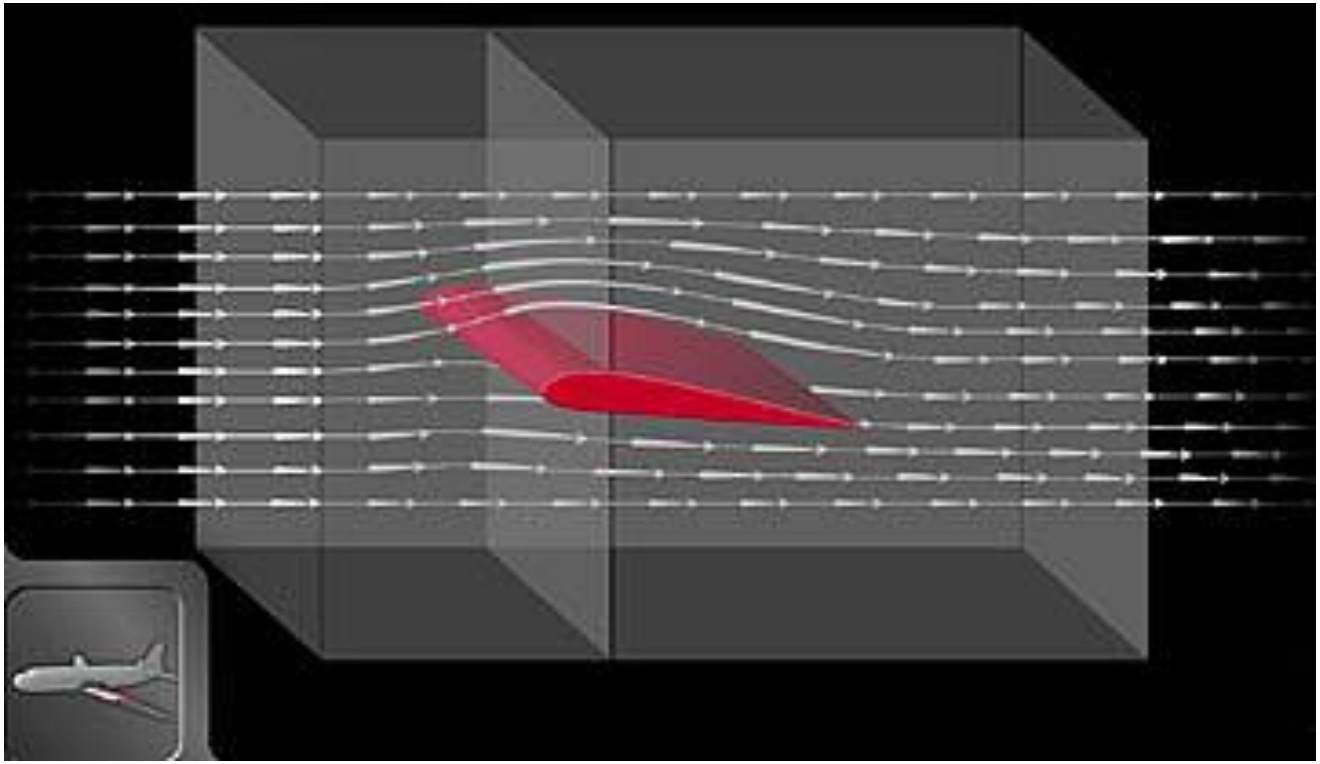
**Weight counteracts lift.**



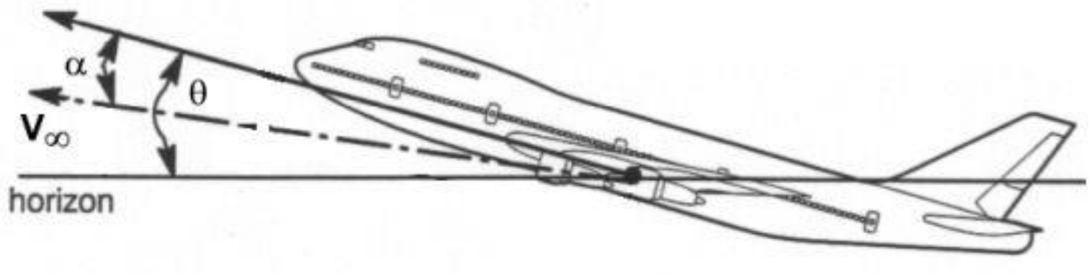
Bernoulli's Principle: slower moving air below the wing creates greater pressure and pushes up.

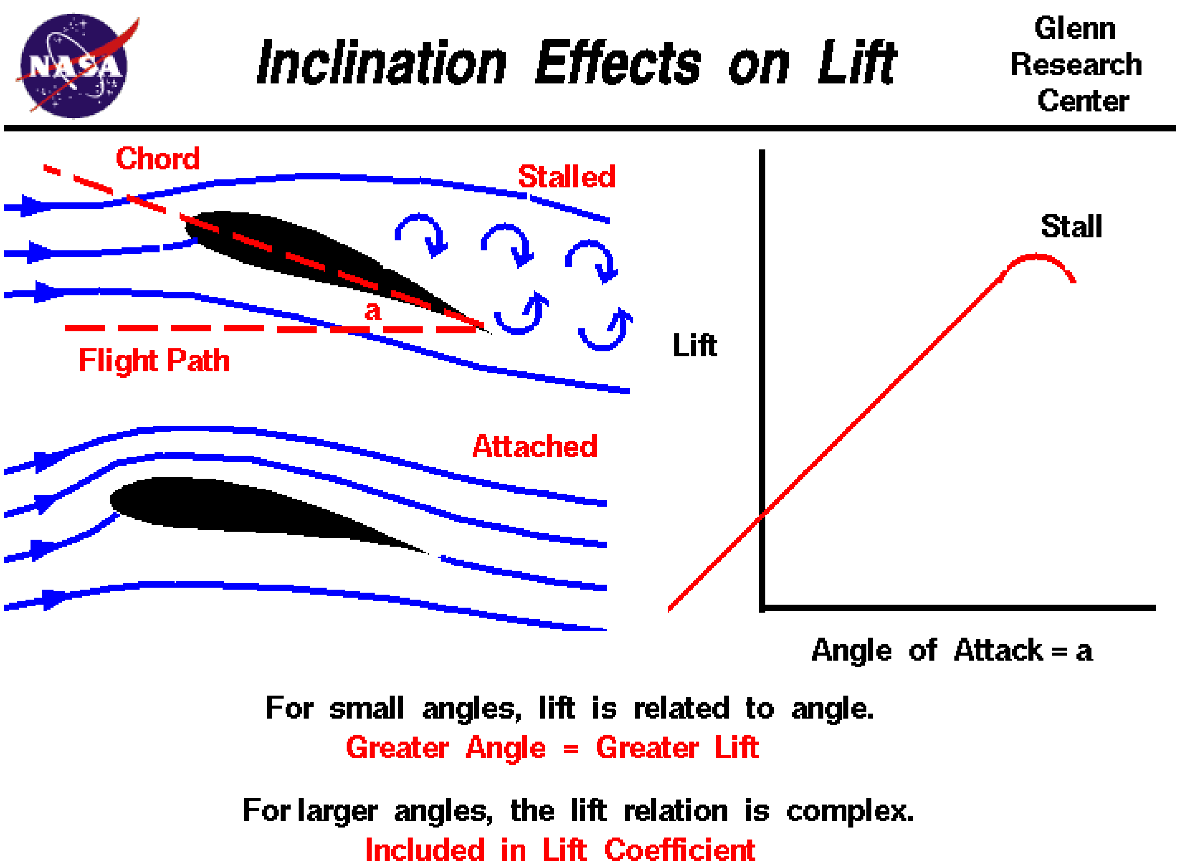


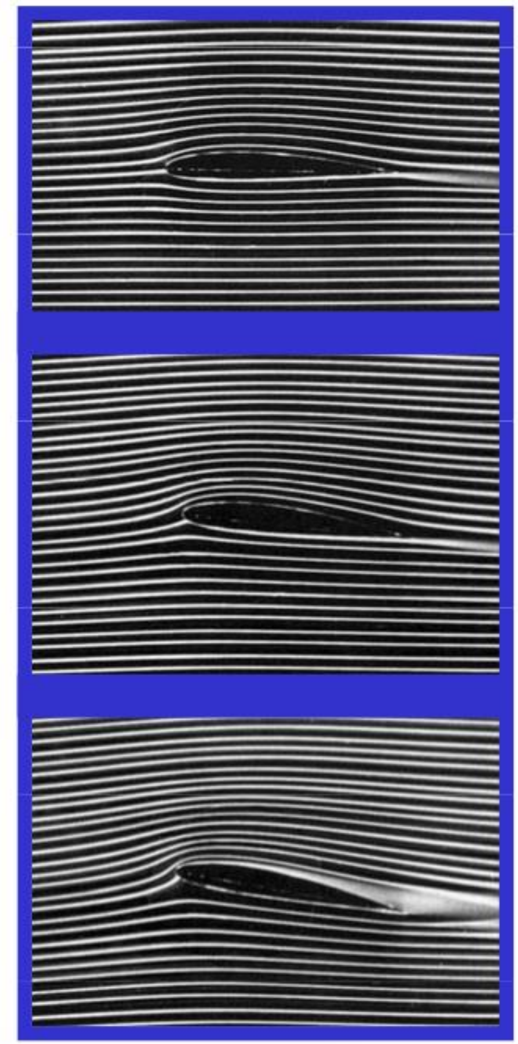
Bernoulli’s Principle: Air moving over the wing moves faster than the air below. Faster-moving air above exerts less pressure on the wing than the slower-moving air below. The result is an upward push on the wing--lift!



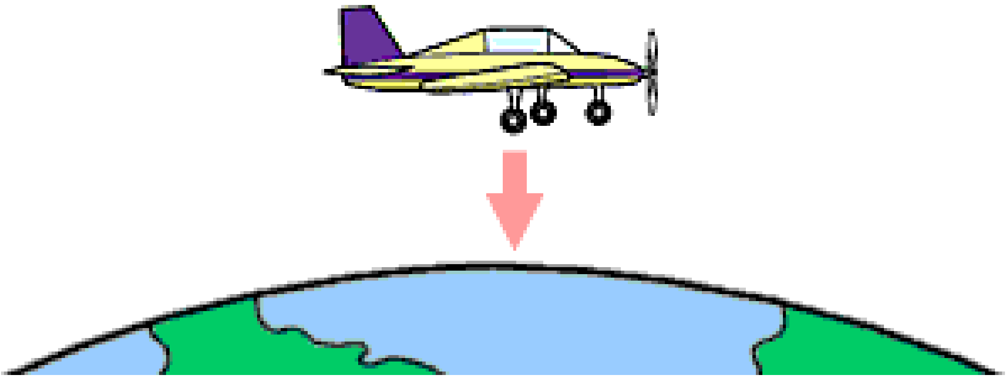
# Lift vs Angle of attack



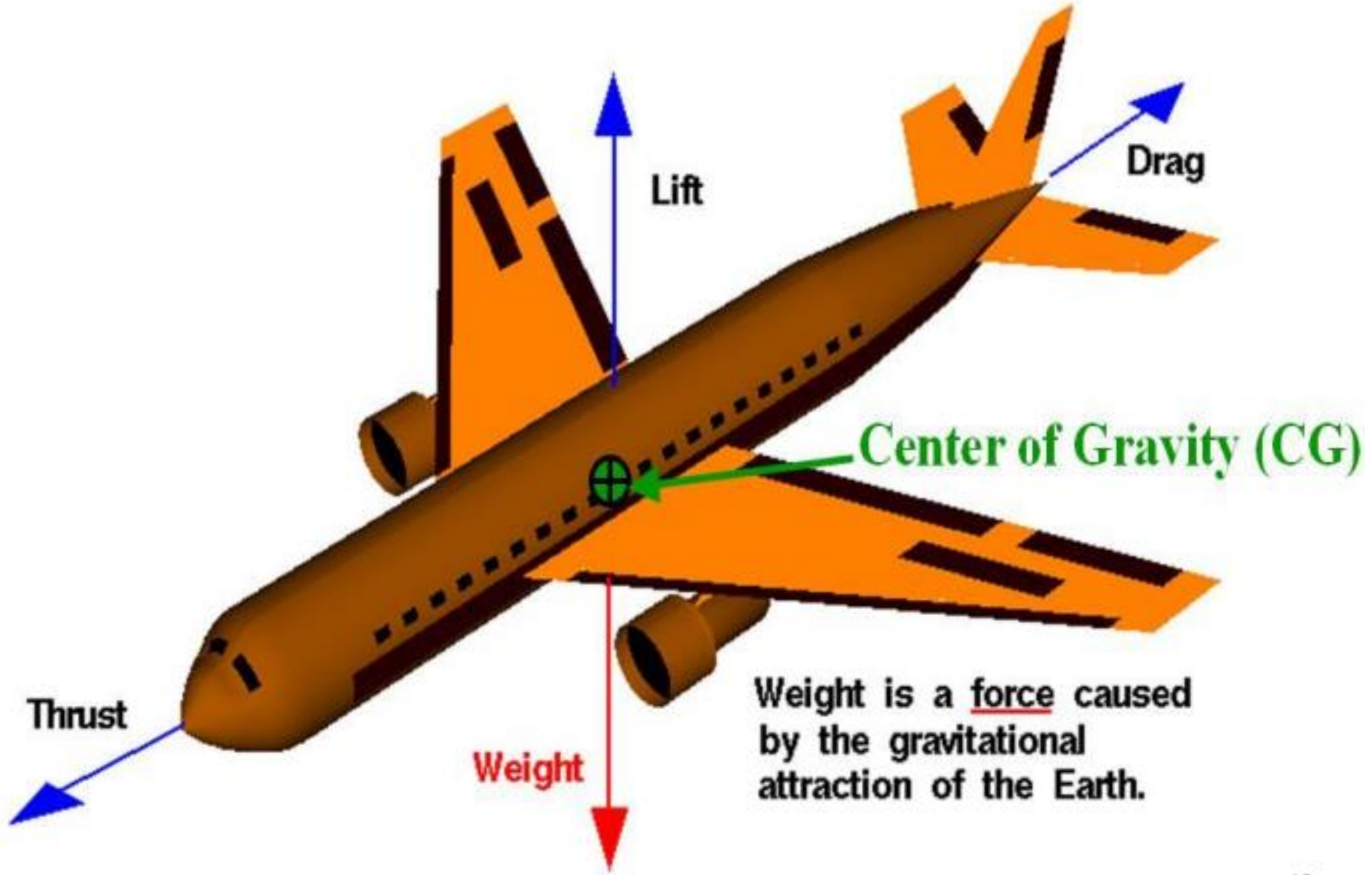



How is the weight of the airplane calculated?

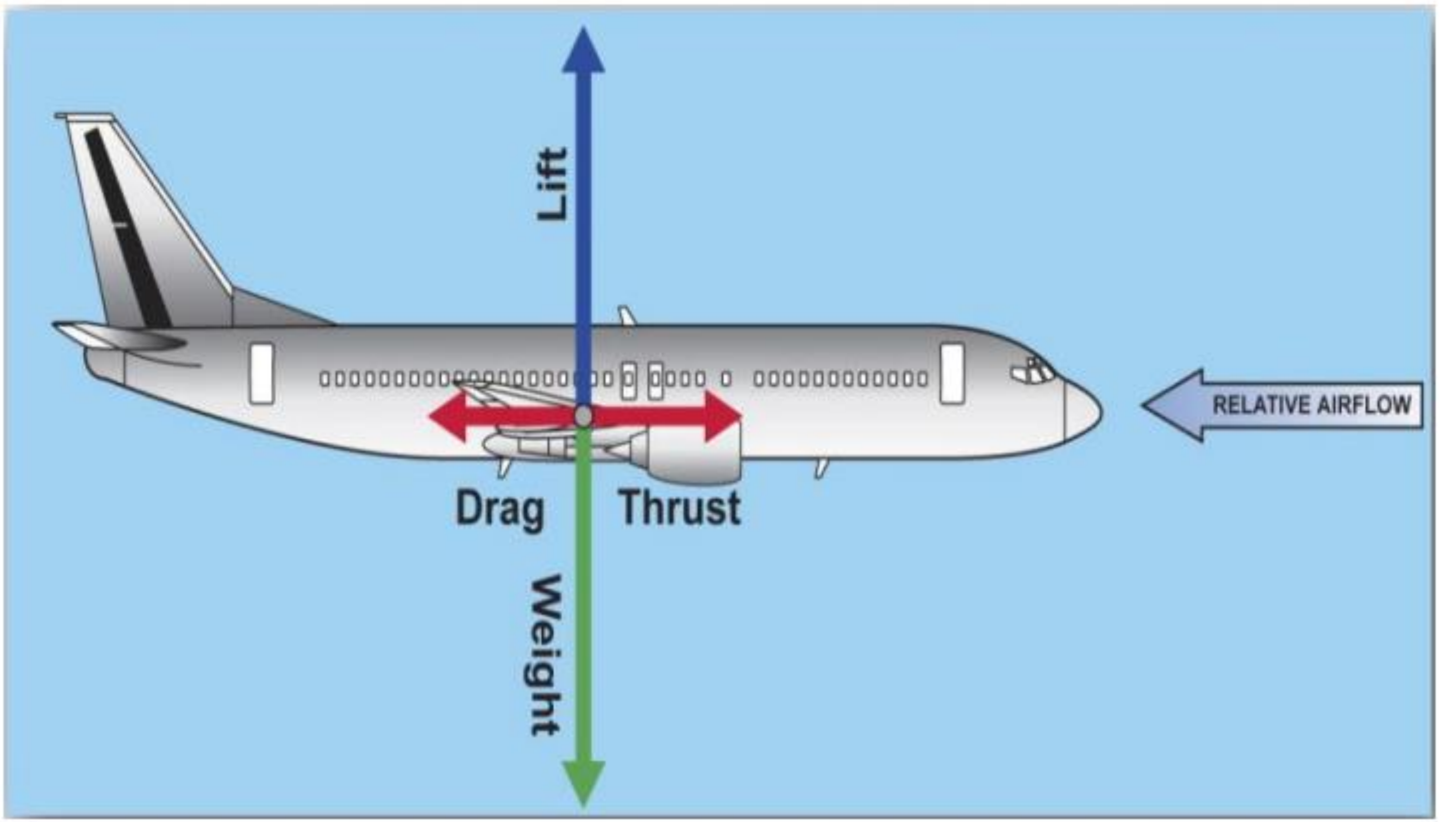


# Forces on an Airplane

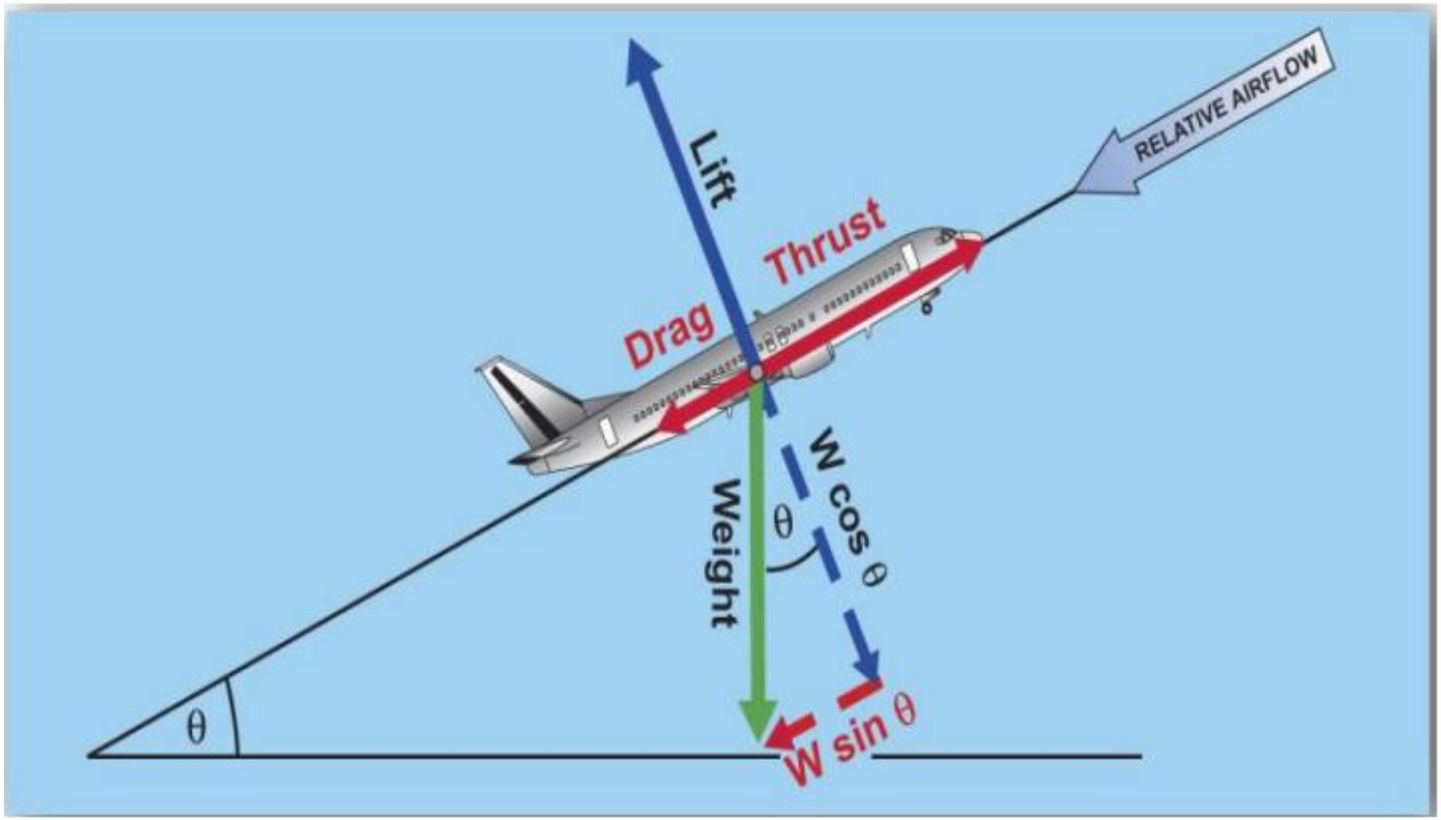



Weight is a force caused by the gravitational attraction of the Earth.

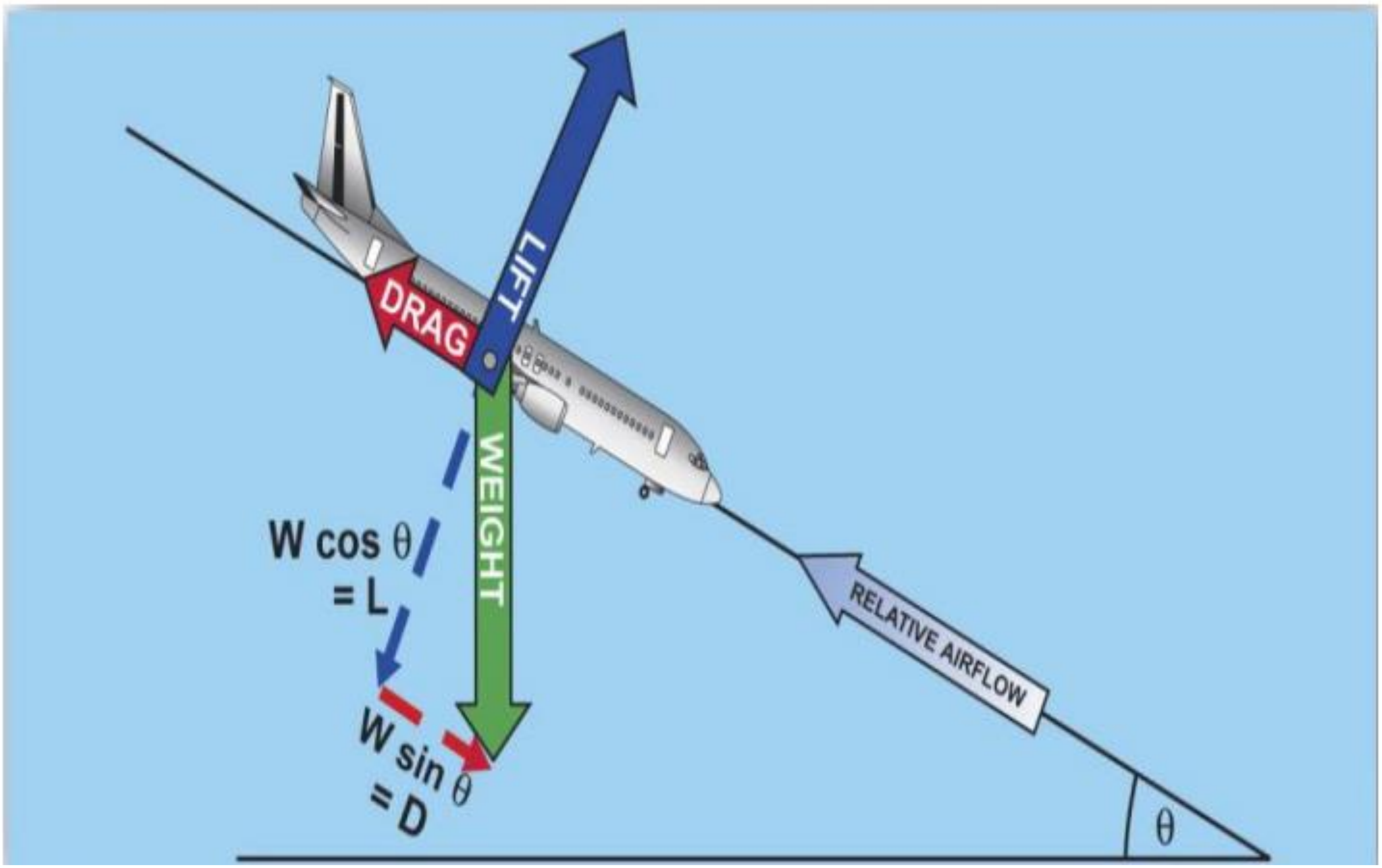
# The Main Four Forces on an Airplane



# The Main Four Forces on an Airplane



# The Main Four Forces on an Airplane



# What is Drag?

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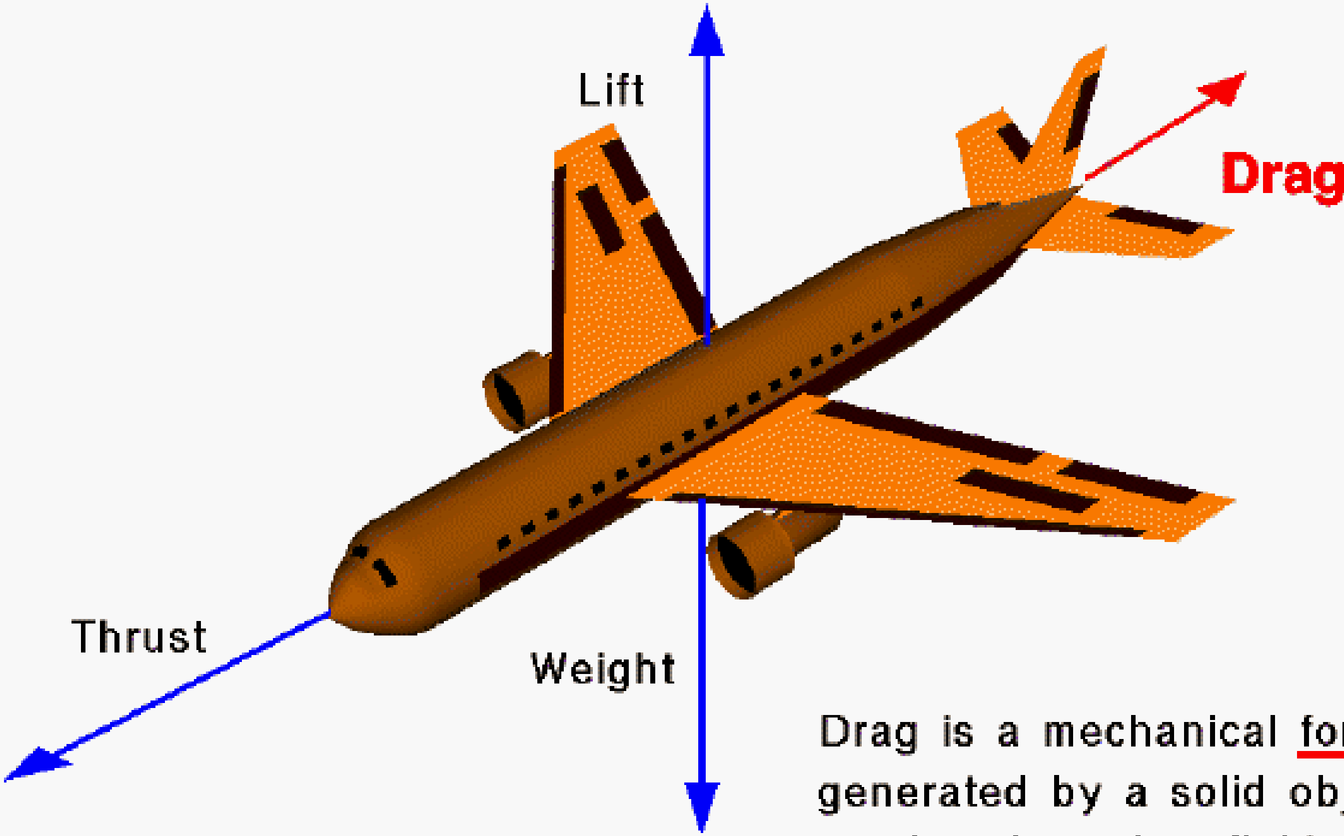
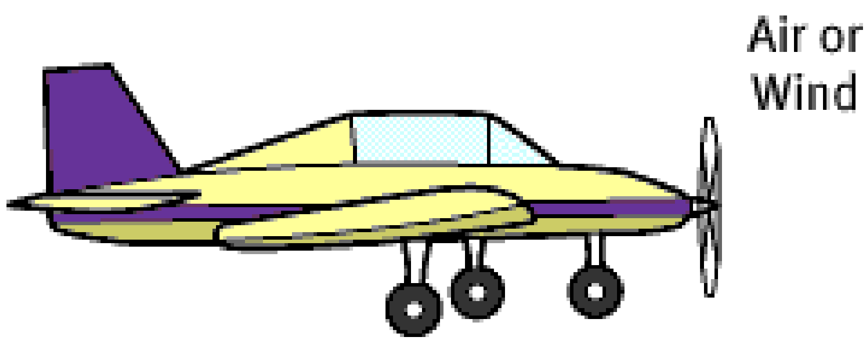
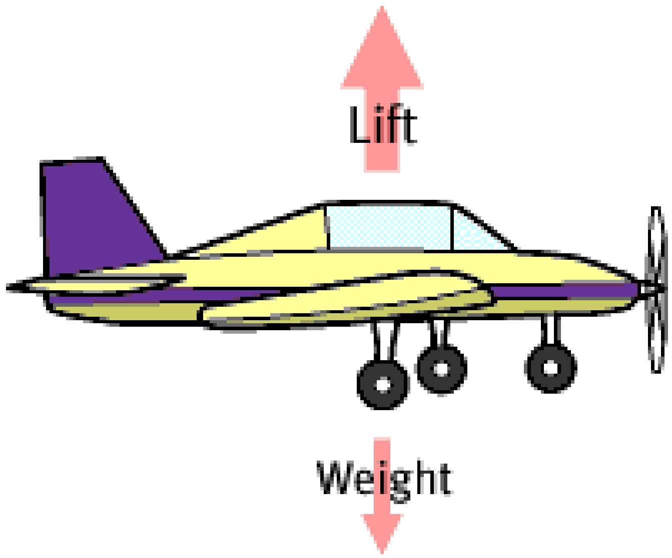



Drag is a mechanical force generated by a solid object moving through a fluid.

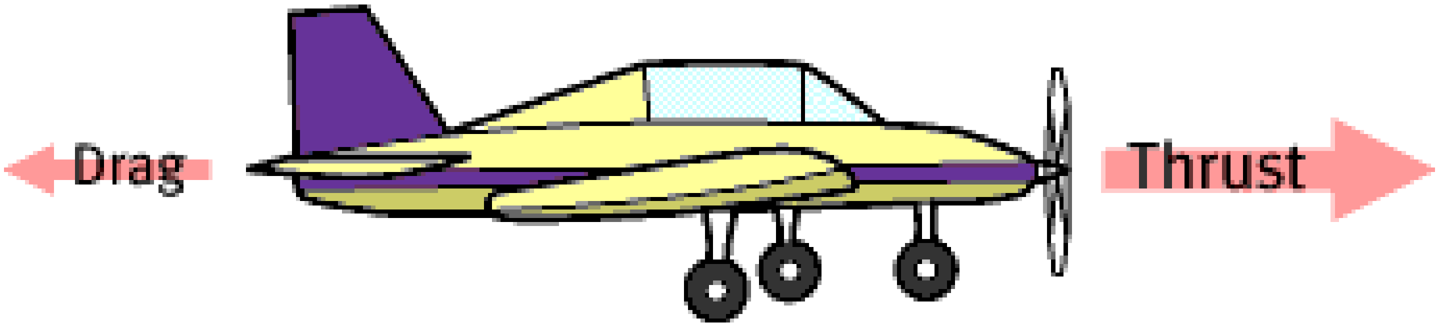
Drag is the force of resistance an aircraft ‘feels’ as it moves through the air.



For an airplane to take off, lift must be greater than weight.

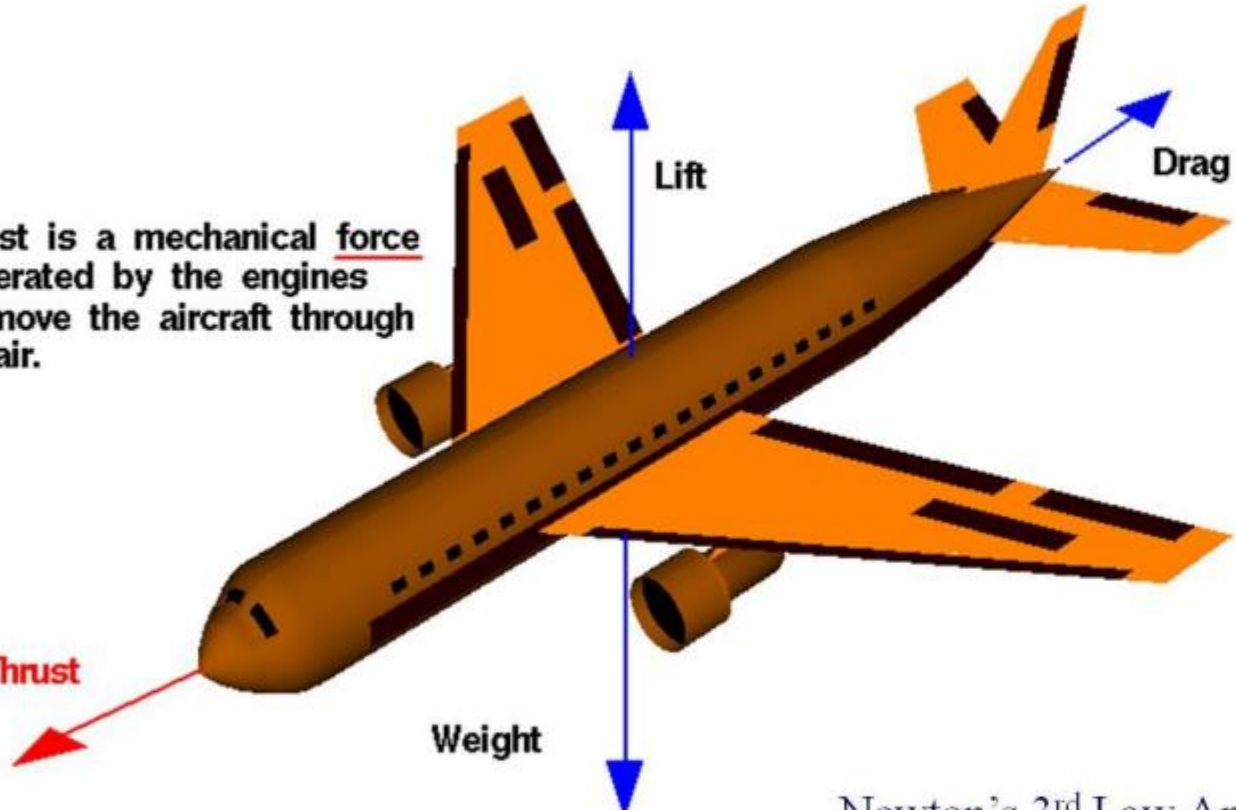



For an airplane to speed up while flying, thrust must be greater than drag.



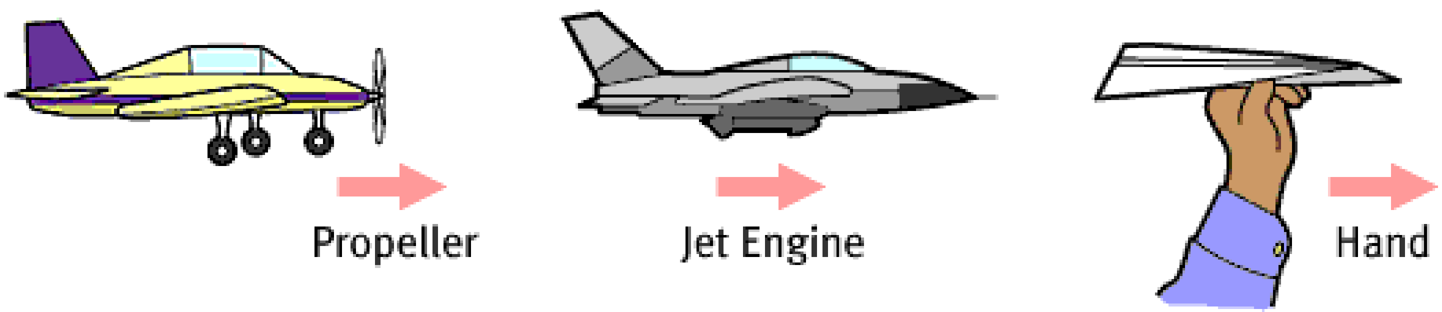
# What is Thrust?

Thrust is a mechanical force generated by the engines to move the aircraft through the air.




Newton's 3rd Law Applies

Engines (either jet or propeller) typically provide the thrust for aircraft. When you fly a paper airplane, you generate the thrust.



# *Propeller Propulsion*

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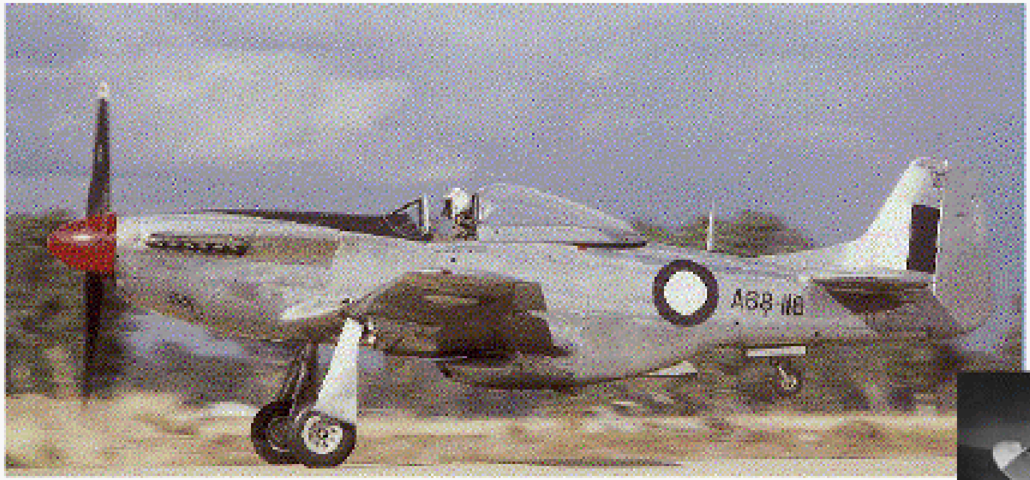



P–51 Mustang

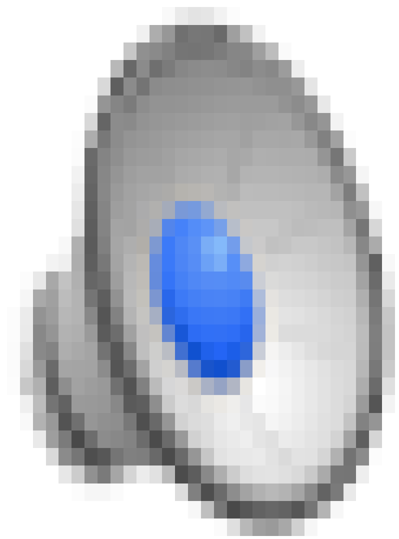
Wind Tunnel Test

# Jet Engine

# Jet Engine

# Jet Engine

# Jet Engine



# Jet Engine

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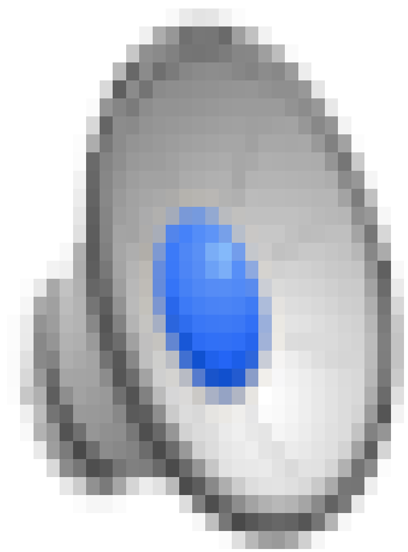
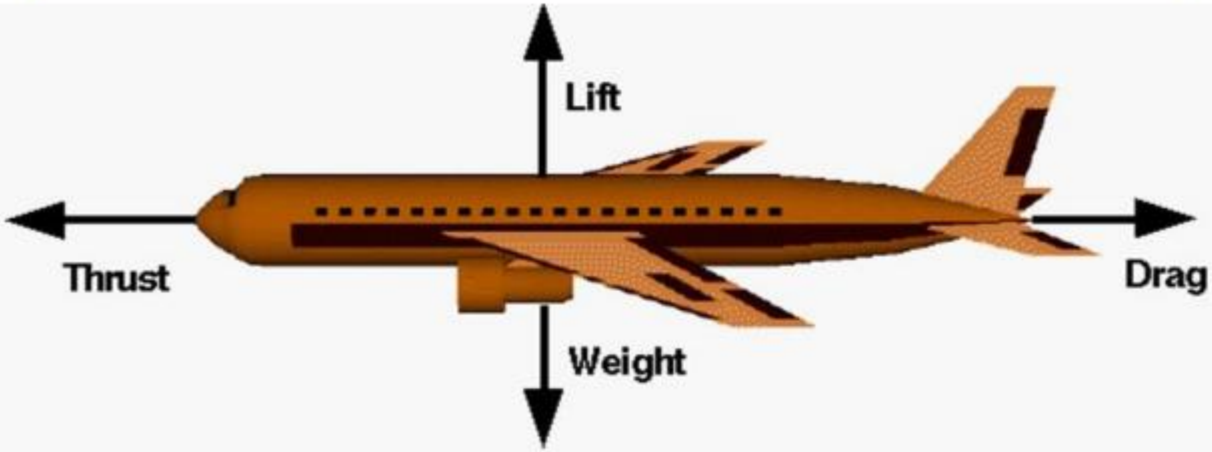
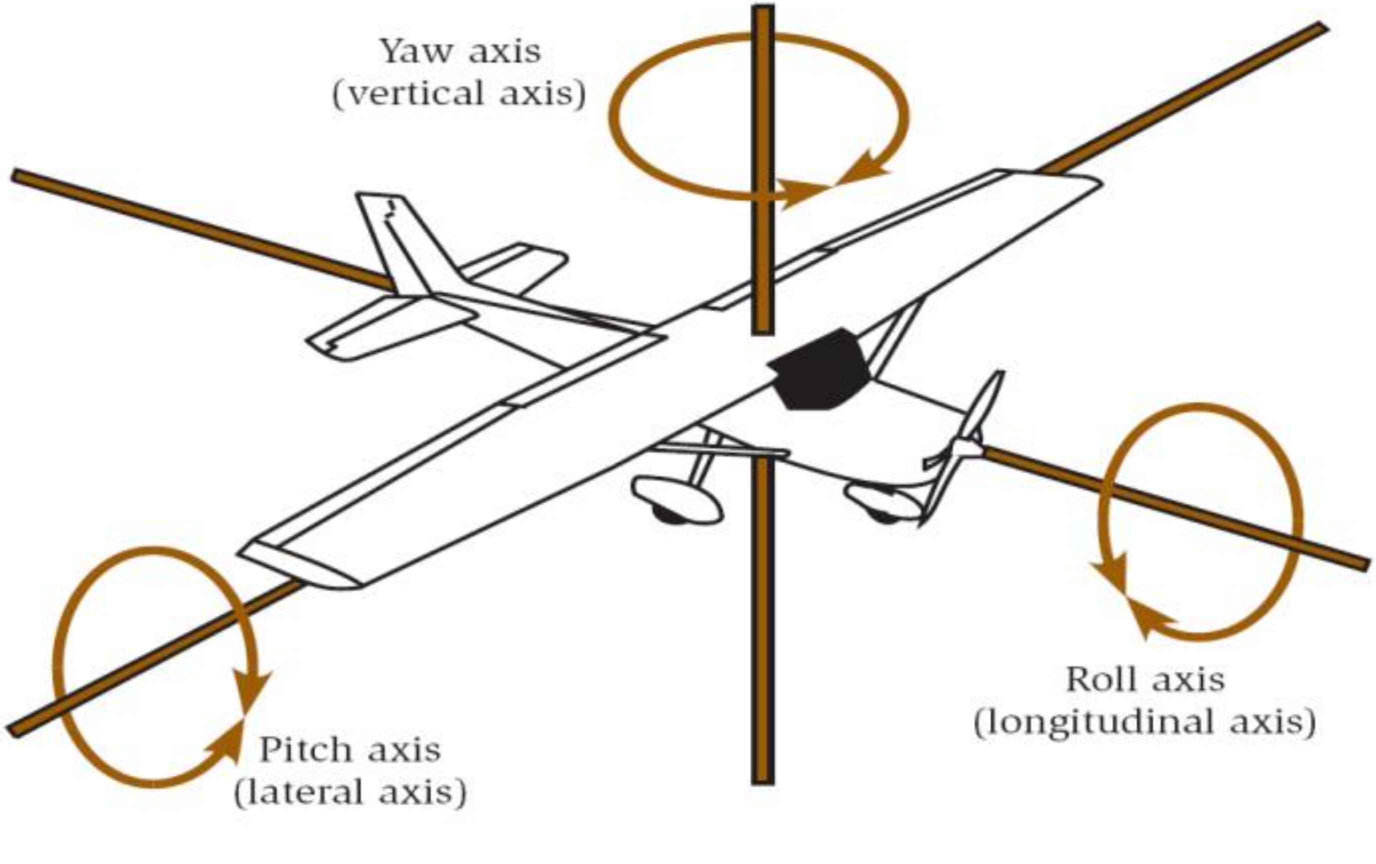


# Simplified Aircraft Motion

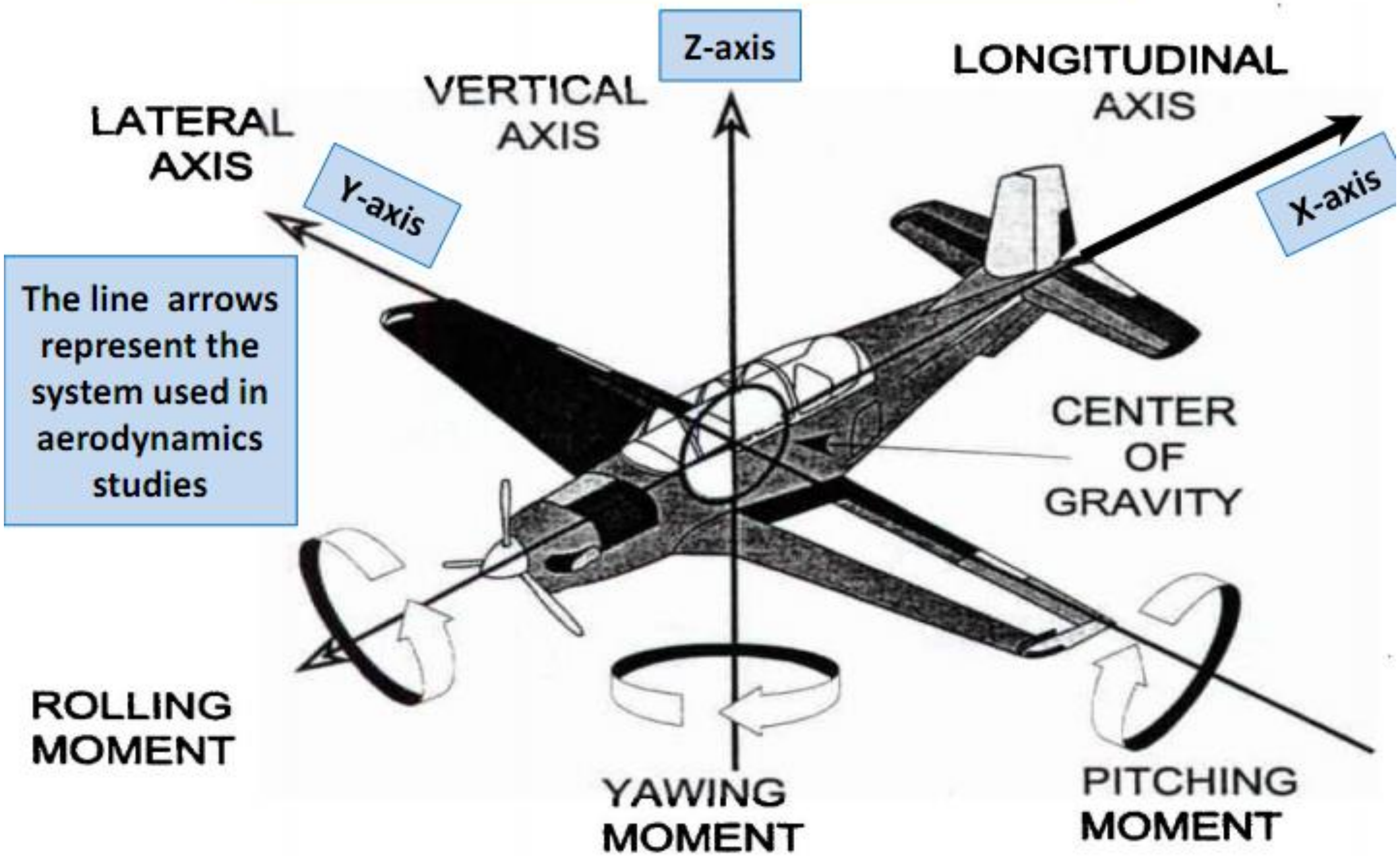



| Flight Condition | Effect |
|---|---|
| Lift > Weight | Plane Rises |
| Weight > Lift | Plane Falls |
| Drag > Thrust | Plane Slows |
| Thrust > Drag | Plane Accelerates |

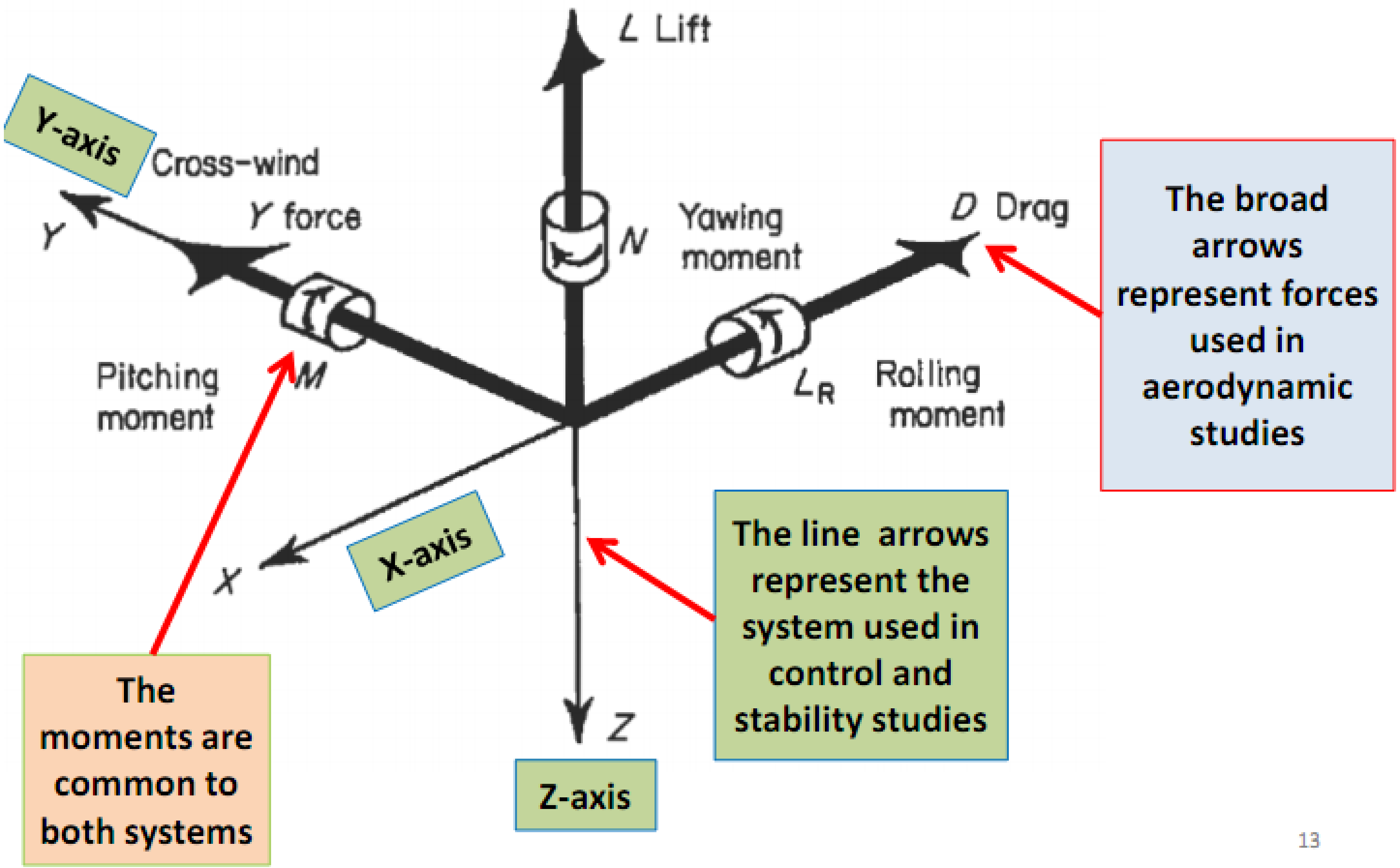
# Axis of rotation of an Airplane



# Moments on an Airplane



# The systems of force and moment components



- However, determining the aerodynamics of a vehicle (finding the lift and drag) is one of the most difficult things you will ever do in engineering, requiring complex theories, experiments in wind tunnels, and simulations using modern highspeed computers.

- However, determining the aerodynamics of a vehicle (finding the lift and drag) is one of the most difficult things you will ever do in engineering, requiring complex theories, experiments in wind tunnels, and simulations using modern highspeed computers.
- In order to prepare you for the challenge of learning about aerodynamics, we will first look at some interesting aspects of aircraft performance, and how we could determine if one airplane will outperform another airplane in a dog fight. Hopefully this will lead us to the point where we realize that aerodynamics is one of the prime characteristics of an airplane, which will determine the performance of the vehicle.

## Example 1

Compare the total energy of a B-52 (shown in Fig. a) that weighs 450,000 Pounds (204,117 kg) and that is cruising at a true air speed of 250 knots (128.8 m/sec, 422.5 ft/sec) at an altitude of 20,000 ft ( 6.1 Km) with the total energy of an F-5 (shown in Fig. b ) that weighs 12,000 pounds (5443.1 kg)and that is cruising at a true air speed of 250 knots at an altitude of 20,000 ft. The equation for the total energy is

$$E = \frac{1}{2}mV^2 + mgh \tag{1.1}$$

(a) B-52H

(b) F-5E

## Example 1.1

The total energy for the B-52 is:

$$E = 0.5 \times 204117 \times 128.8^2 + 204117 \times 9.8 \times 6.1 \times 1000$$

$$E = 1.3894 \times 10^{10}\, Joule$$

The total energy for the F-5 is:

$$E = 0.5 \times 5443.1 \times 128.8^2 + 5443.1 \times 9.8 \times 6.1 \times 1000$$

$$E = 3.7 \times 10^{8}\, Joule$$

The total energy of the B-52 is 37.5 times the total energy of the F-5.

## Example 1.2: The Energy Height

Since the weight specific energy also has units of height, it will be given the symbol *He* and is called the energy height. Dividing the terms in equation (1.1) by the weight of the aircraft (W = m/g).

$$H_e = \frac{E}{W} = \frac{V^2}{2g} + h \qquad \mathbf{(1.3)}$$

Compare the energy height of a B-52 flying at 250 knots at an altitude of 20,000 ft with that of an F-5 cruising at the same altitude and at the same velocity.

**Solution**

The energy height of the B-52 is

$$H_e = 0.5 \times 128.8^2/9.8 + 6.1 \times 1000$$
$$H_e = 6.941 \times 10^3\ m$$

Since the F-5 is cruising at the same altitude and at the same true air speed as the B-52, it has the same energy height.

If we consider only this weight specific energy, the B-52 and the F-5 are equivalent.

# Captain Oswald Boelcke Combat 5 Rules

1. Always try to secure an advantageous position before attacking. Climb before and during the approach in order to surprise the enemy from above, and dive on him swiftly from the rear when the moment to attack is at hand.
2. Try to place yourself between the sun and the enemy. This puts the glare of the sun in the enemy’s eyes and makes it difficult to see you and impossible to shoot with any accuracy.
3. Do not fire the machine guns until the enemy is within range and you have him squarely within your sights.
4. Attack when the enemy least expects it or when he is preoccupied with other duties, such as observation, photography, or bombing.
5. Never turn your back and try to run away from an enemy fighter. If you are surprised by an attack on your tail, turn and face the enemy with your guns.

## Specific Excess Power ($P_s$)

- The power either to accelerate.
- Consider the  case where the F-5 is flying at a constant altitude. If the engine is capable of generating more thrust than the drag acting on the aircraft, the acceleration of the aircraft can be calculated using Newton's Law:

$$\sum F = m\,a$$

which for an aircraft accelerating at a constant altitude becomes

$$T - D = \frac{W}{g}\frac{dV}{dt} \qquad \textbf{(1.4)}$$

Multiplying both sides of equation (1.4) by V and dividing by W gives

$$P_s = \frac{(T - D)V}{W} = \frac{V}{g}\frac{dV}{dt} \qquad \textbf{(1.5)}$$

which is the specific excess power.

# Example 1.3: The specific excess power and acceleration

- Calculate the maximum acceleration for a 12,000-lbf (53378.6 N) F-5 that is flying at 250 knots (422.5 ft/s) at 20,000 ft (6.1 Km) . it is capable of generating 3550 lbf (15791 N) thrust ( T ) with the afterburner lit, while the total drag ( D ) acting on the aircraft is 1750 lbf (7784.3 N). Thus, the specific excess power is

$$P_s = \frac{(T-D)V}{W} = \frac{(15791 - 7784.3) \times 128.8}{53378.6} = 19.45\ m/sec$$

Rearranging equation (1.5) to solve for the acceleration gives

$$Acceleration = \frac{dV}{dt} = P_s \frac{g}{V} = 19.45 \times \frac{9.8}{128.8} = 1.47\ m/sec^2$$

# Using Specific Excess Power to Change the Energy Height

Taking the derivative with respect to time of the two terms in equation (1.3), we obtain:

$$\frac{dH_e}{dt} = \frac{V}{g}\frac{dV}{dt} + \frac{dh}{dt} \qquad \textbf{(1.6)}$$

The first term on the

change of kinetic energy (per unit weight). It is a function of the rate of change of the velocity as seen by the pilot *dV/dt.* The significance of the second term is even less cosmic. It is the rate of change of the potential energy (per unit weight). Note also that *dh/dt* is the vertical component of the velocity [i.e., the rate of climb (ROC)] as seen by the pilot on his altimeter. Combining the logic that led us to equations (1.5) and (1.6) leads us to the conclusion that the specific excess power is equal to the time-rate-of-change of the energy height.

So,

$$H_e = \frac{E}{W} = \frac{V^2}{2g} + h \qquad \textbf{(1.3)}$$

$$P_s = \frac{(T-D)V}{W} = \frac{V}{g}\frac{dV}{dt} \qquad \textbf{(1.5)}$$

$$P_s = \frac{(T-D)V}{W} = \frac{dH_e}{dt} = \frac{V}{g}\frac{dV}{dt} + \frac{dh}{dt} \qquad \textbf{(1.7)}$$

Given the specific excess power calculated in Example 1.3 , we could use equation (1.7) to calculate the maximum rate-of-climb (for a constant velocity) for the (53378.6 N) F-5 as it passes through 20,000 ft (6.1 Km) at 250 knots (128.8 m/sec).

$$P_s = \frac{(T - D)V}{W} = \frac{dH_e}{dt} = \frac{V}{g}\frac{dV}{dt} + \frac{dh}{dt} \qquad \mathbf{(1.7)}$$

$$\frac{dh}{dt} = P_s = \frac{(15791 - 7784.3) \times 128.8}{53378.6} = 19.45\ m/sec$$

- A small aircraft could enjoy a high thrust-to-weight ratio: small aircraft have less drag.
- “The original F-16 design had about one-third the drag of an F-4 in level flight and one-fifteenth the drag of an F-4 at a high angle-of attack”

## Terminology in Manuverability

- Lift
- Drag
- Range
- Rate of climb
- Glide ratio (which is exactly the lift/drag ratio of the airplane).

Without knowing the aerodynamics of the airplane (as well as the mass properties and thrust), we will not be able to determine how well an airplane will perform. This requires knowing the flow field around the airplane so that the pressures, shear stress, and heating on the surface of the airplane can be determined. That is why the study of aerodynamics is an essential stepping stone to gaining a fuller understanding of how an airplane will perform, and how to improve that performance to achieve flight requirements.

# SOLVING FOR THE AEROTHERMODYNAMIC PARAMETERS

The fundamental problem facing the aerodynamicist is to predict the aerodynamic forces and moments and the heat-transfer rates acting on a vehicle in flight. In order to predict these aerodynamic forces and moments with suitable accuracy, it is necessary to be able to describe the pattern of flow around the vehicle. The resultant flow pattern depends on the geometry of the vehicle, its orientation with respect to the undisturbed free stream, and the altitude and speed at which the vehicle is traveling.

## Concept of a Fluid

From the point of view of fluid mechanics, matter can be in one of two states—either solid or fluid. The technical distinction between these two states lies in their response to an applied shear, or tangential, stress. A solid can resist a shear stress by a static deformation; a fluid cannot. A *fluid* is a substance that deforms continuously under the action of shearing forces.

A fluid can be either a liquid or a gas. A liquid is composed of relatively closely packed molecules with strong cohesive forces. As a result, a given mass of liquid will occupy a definite volume of space. If a liquid is poured into a container, it assumes the shape of the container up to the volume it occupies and will form a free surface in a gravitational field if unconfined from above.

Gas molecules are widely spaced with relatively small cohesive forces. Therefore, if a gas is placed in a closed container, it will expand until it fills the entire volume of the container

## Concept of a Fluid

There are two basic ways to develop equations that describe the motion of a system of fluid particles: we can either define the motion of each and every molecule or define the average behavior of the molecules within a given elemental volume.
Our primary concern for problems in this text will not be with the motion of individual molecules, but with the general behavior of the fluid. We are concerned with describing the fluid motion in physical spaces that are very large compared to molecular dimensions (the size of molecules).

## Fluid Properties

*Temperature: (C, K)*
*Pressure:* the magnitude of this force per unit area of surface ($N/m^2$, Pa).

*Standard atmospheric pressure at sea level* is defined as the pressure that can support a column of mercury 760 mm in length when the density of the mercury is 13.5951 $g/cm^3$ and the acceleration due to gravity is the standard sea level value. The standard atmospheric pressure at sea level in SI (System International) units is $1.01325 * 10^5$ $N/m^2$.

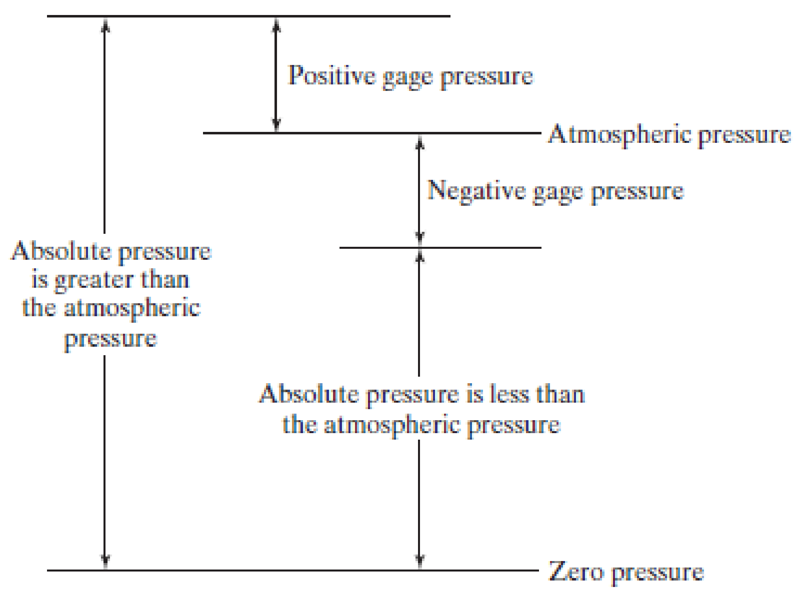



**Figure 1.3** Terms used in pressure measurements.

# Fluid Properties

*Density:* the mass of the fluid per unit Volume (kg/m$^3$)

For a thermally perfect gas, the equation of state is

$$\rho = \frac{p}{RT}$$

The gas constant *R* has a particular value for each substance. The gas constant for air has the value 287.05 N . m /kg . K

The density of air at standard day sea level conditions is 1.2250 kg/ m3

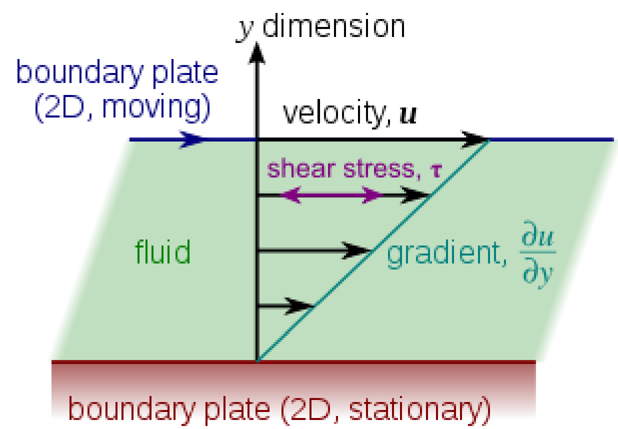
# Fluid Properties

*Viscosity:* In all real fluids, a shearing deformation is accompanied by a shearing stress. The fluids of interest in this text are *Newtonian* in nature; that is, the shearing stress is proportional to the rate of shearing deformation. The constant of proportionality is called the *coefficient of viscosity* , m. Therefore,

$$\text{shear stress} = \mu \times \text{transverse gradient of velocity}$$

The viscosity of air is independent of pressure for temperatures below 3000 K (5400°R). In this temperature range, we could use Sutherland's equation to calculate the coefficient of viscosity:

$$\mu = C_1 \frac{T^{1.5}}{T + C_2}$$




For SI units where temperature, *T* , is in units of K and m is in units of kg/s # m use $C_1$ = 1.458 * $10^{-6}$ and $C_2$ = 110.4 .

## Fluid Properties

*Kinematic Viscosity: T*he ratio:

$$\nu = \frac{\mu}{\rho}$$

*Speed of sound:* The speed at which a disturbance of infinitesimal proportions propagates through a fluid that is at rest is known as the *speed of sound* , which is designated in this book as *a* (the acoustic speed). The speed of sound is established by the properties of the fluid. For a perfect gas

$$a = \sqrt{\gamma RT}$$

where $\gamma$ is the ratio of specific heats (Cp/Cv) and *R* is the gas constant. For the range of temperature over which air behaves as a perfect gas, g = 1.4 and the speed of sound is given by

$$a = 20.047\sqrt{T}$$

where *T* is the temperature in K and the units for the speed of sound are m/s

## Pressure Variation in a Static Fluid Medium

In order to compute the forces and moments or the heat-transfer rates acting on a vehicle, or to determine the flight path (i.e., the trajectory) of the vehicle, we will often need an analytic model of the atmosphere instead of using a table, such as Table 1.2 .

**TABLE 1.2A** U.S. Standard Atmosphere, 1976 SI Units

| *Geometric Altitude (km)* | *Pressure ($N/m^2$)* | *Temperature (K)* | *Density ($kg/m^3$)* | *Viscosity ($kg/m \cdot s$)* | *Speed of Sound (m/s)* |
|---|---|---|---|---|---|
| 0 | 1.0133 E + 05 | 288.150 | 1.2250 E + 00 | 1.7894 E − 05 | 340.29 |
| 1 | 8.9875 E + 04 | 281.651 | 1.1117 E + 00 | 1.7579 E − 05 | 336.43 |
| 2 | 7.9501 E + 04 | 275.154 | 1.0066 E + 00 | 1.7260 E − 05 | 332.53 |
| 3 | 7.0121 E + 04 | 268.659 | 9.0926 E − 01 | 1.6938 E − 05 | 328.58 |
| 4 | 6.1669 E + 04 | 262.166 | 8.1934 E − 01 | 1.6612 E − 05 | 324.59 |
| 5 | 5.4048 E + 04 | 255.676 | 7.3643 E − 01 | 1.7885 E − 05 | 320.55 |
| 6 | 4.7217 E + 04 | 249.187 | 6.6012 E − 01 | 1.5949 E − 05 | 316.45 |
| 7 | 4.1105 E + 04 | 242.700 | 5.9002 E − 01 | 1.5612 E − 05 | 312.31 |
| 8 | 3.5651 E + 04 | 236.215 | 5.2578 E − 01 | 1.5271 E − 05 | 308.11 |
| 9 | 3.0800 E + 04 | 229.733 | 4.6707 E − 01 | 1.4926 E − 05 | 303.85 |
| 10 | 2.6500 E + 04 | 223.252 | 4.1351 E − 01 | 1.4577 E − 05 | 299.53 |
| 11 | 2.2700 E + 04 | 216.774 | 3.6481 E − 01 | 1.4223 E − 05 | 295.15 |
| 12 | 1.9399 E + 04 | 216.650 | 3.1193 E − 01 | 1.4216 E − 05 | 295.07 |
| 13 | 1.6579 E + 04 | 216.650 | 2.6660 E − 01 | 1.4216 E − 05 | 295.07 |

## Pressure Variation in a Static Fluid Medium

$$T = T_0 - Bz \tag{1.21}$$

where $T_0$ is the sea-level temperature (absolute) and $B$ is the lapse rate, both of which vary from day to day. The following standard values will be assumed to apply from 0 to 11,000 m:

$$T_0 = 288.15\ \text{K} \qquad \text{and} \qquad B = 0.0065\ \text{K/m}$$

Substituting equation (1.21) into the relation

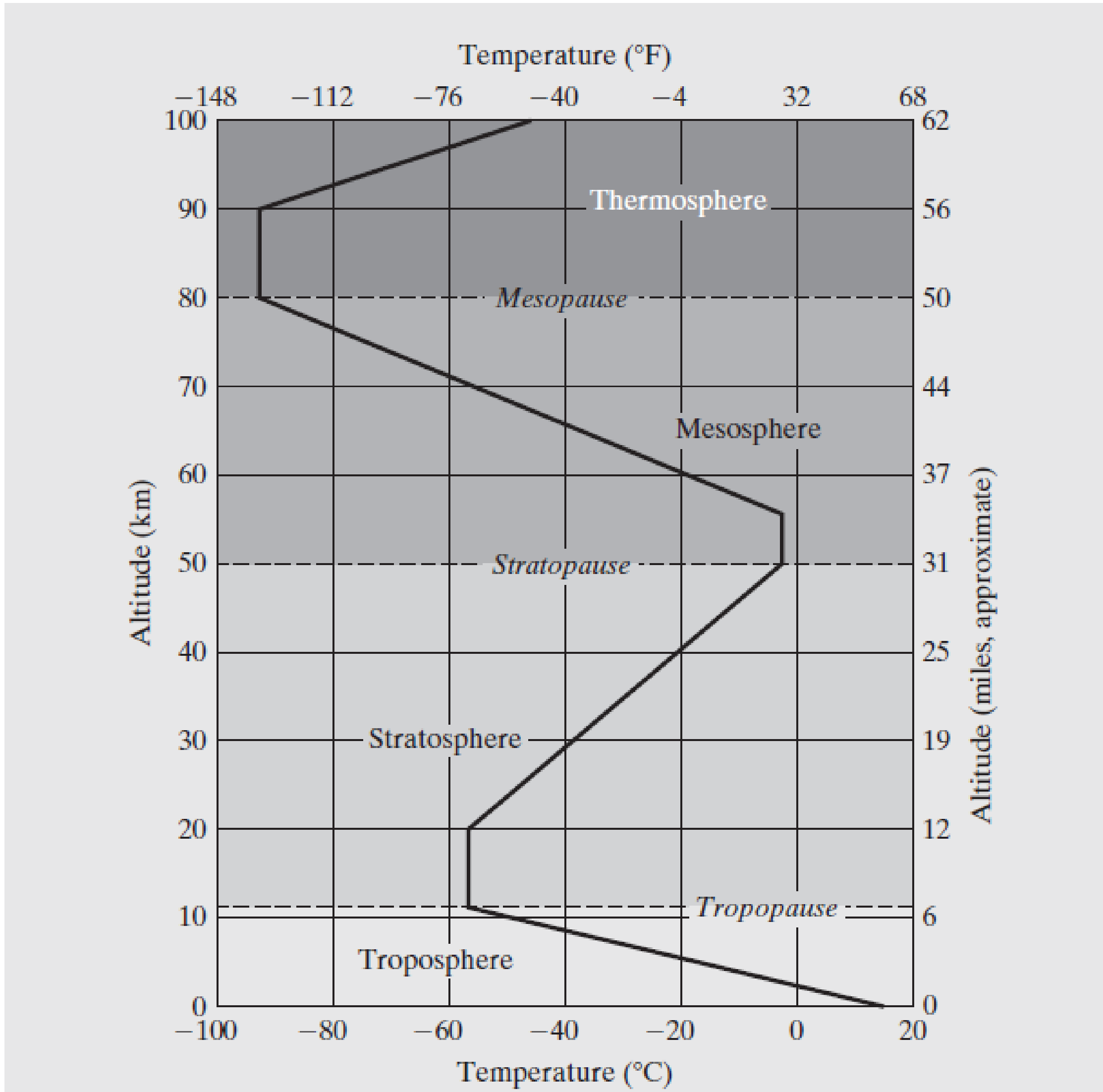
$$\int \frac{dp}{p} = -\int \frac{g\,dz}{RT}$$

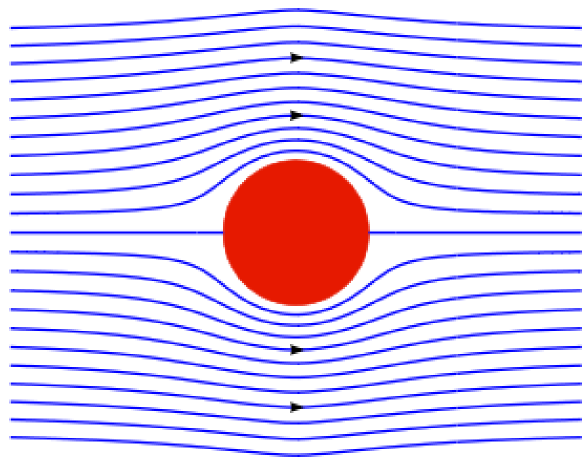
and integrating, we obtain

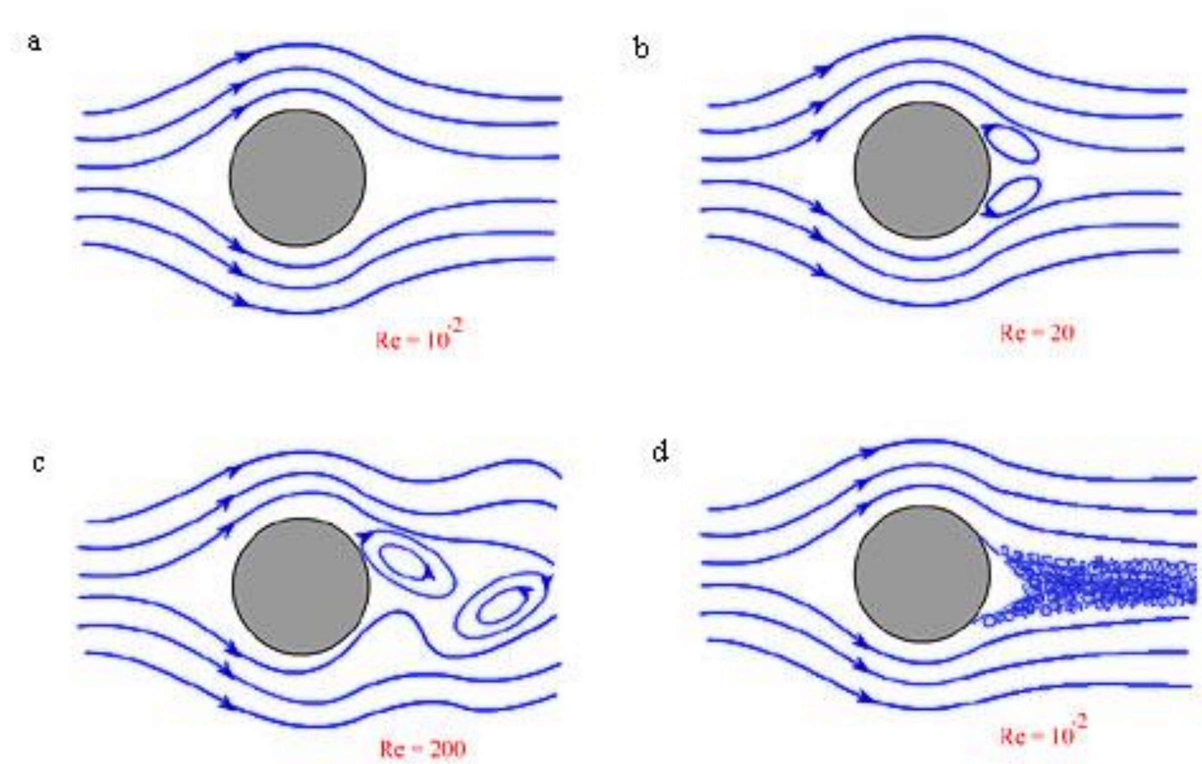
$$p = p_0\left(1 - \frac{Bz}{T_0}\right)^{g/RB} \tag{1.22}$$

The exponent $g/RB$, which is dimensionless, is equal to 5.26 for air.

# Atmospheric layers







a
b
Re = $10^{2}$
Re = 20
c
d
Re = 200
Re = $10^{2}$

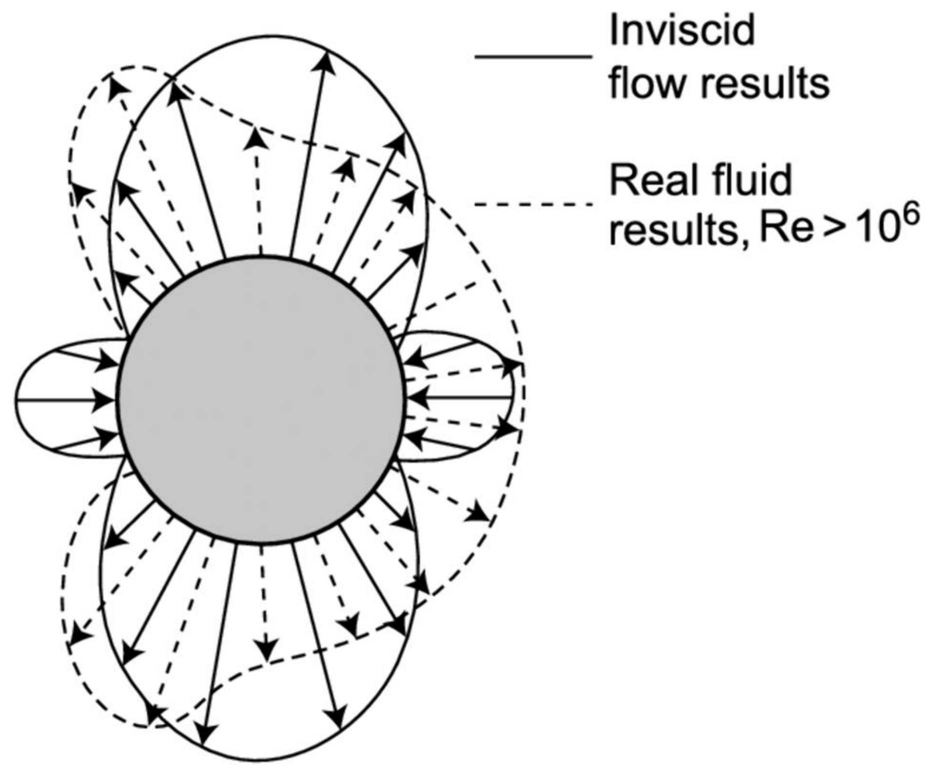



FIGURE 1.16 Pressure on a circular cylinder with its axis normal to the stream (see also Fig. 7.27).

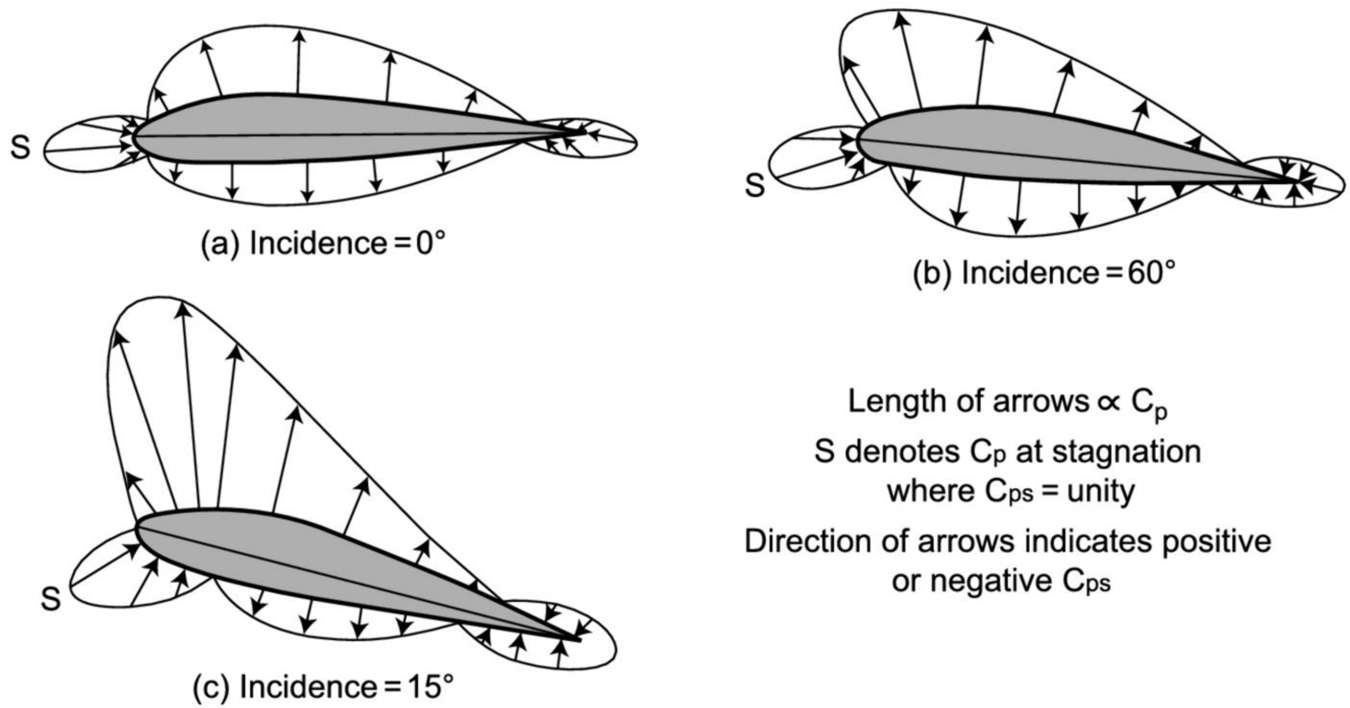



FIGURE 1.9 Typical airfoil pressure distribution.

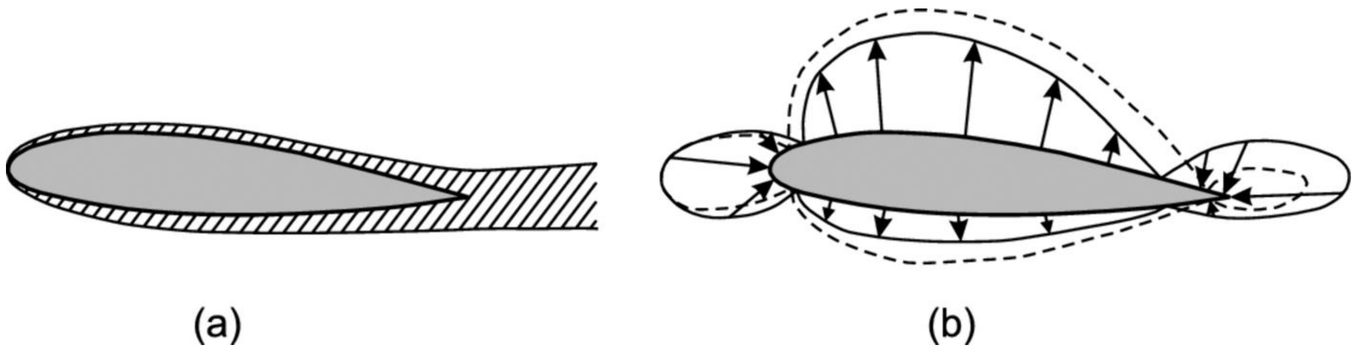



FIGURE 1.13 (a) Displacement thickness of the boundary layer (hatched area) representing an effective change in airfoil shape (boundary-layer thickness is greatly exaggerated). (b) Pressure distribution on an airfoil section in viscous flow (dotted line) and inviscid flow (solid line).

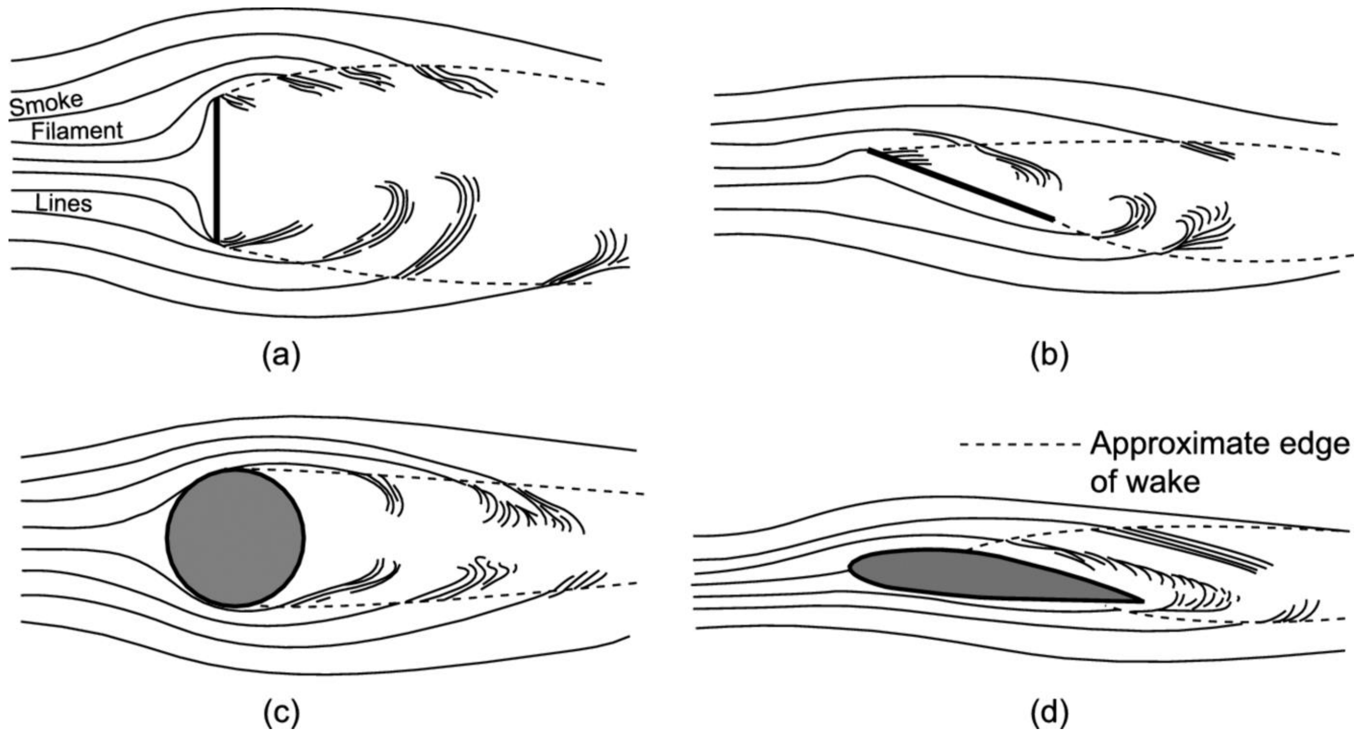



FIGURE 1.17 Behavior of smoke filaments in flows past various bodies, showing wakes. (a) Normal flat plate. In this case the wake oscillates up and down at several cycles per second. Half a cycle later the picture would be reversed, with the upper filaments curving back, as the lower filaments curve in this sketch. (b) Flat plate at fairly high incidence. (c) Circular cylinder at low *Re*. (For a pattern at highest *Re*, see Fig. 3.13.) (d) Airfoil section at moderate incidence and low *Re*.

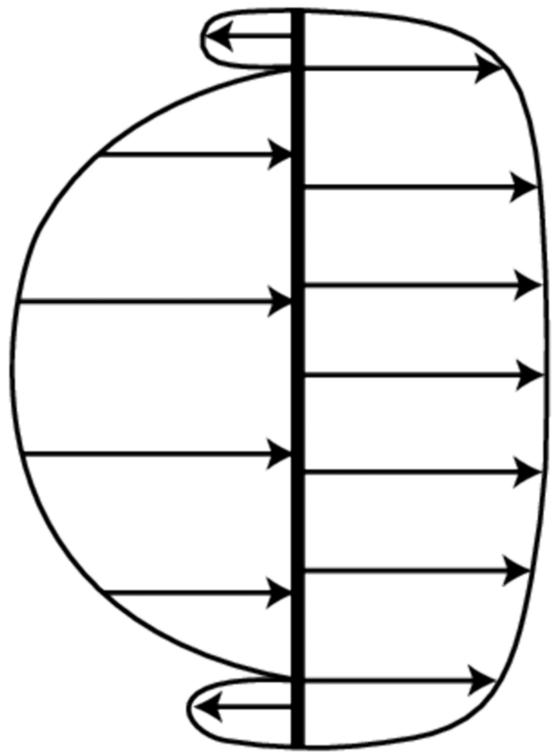
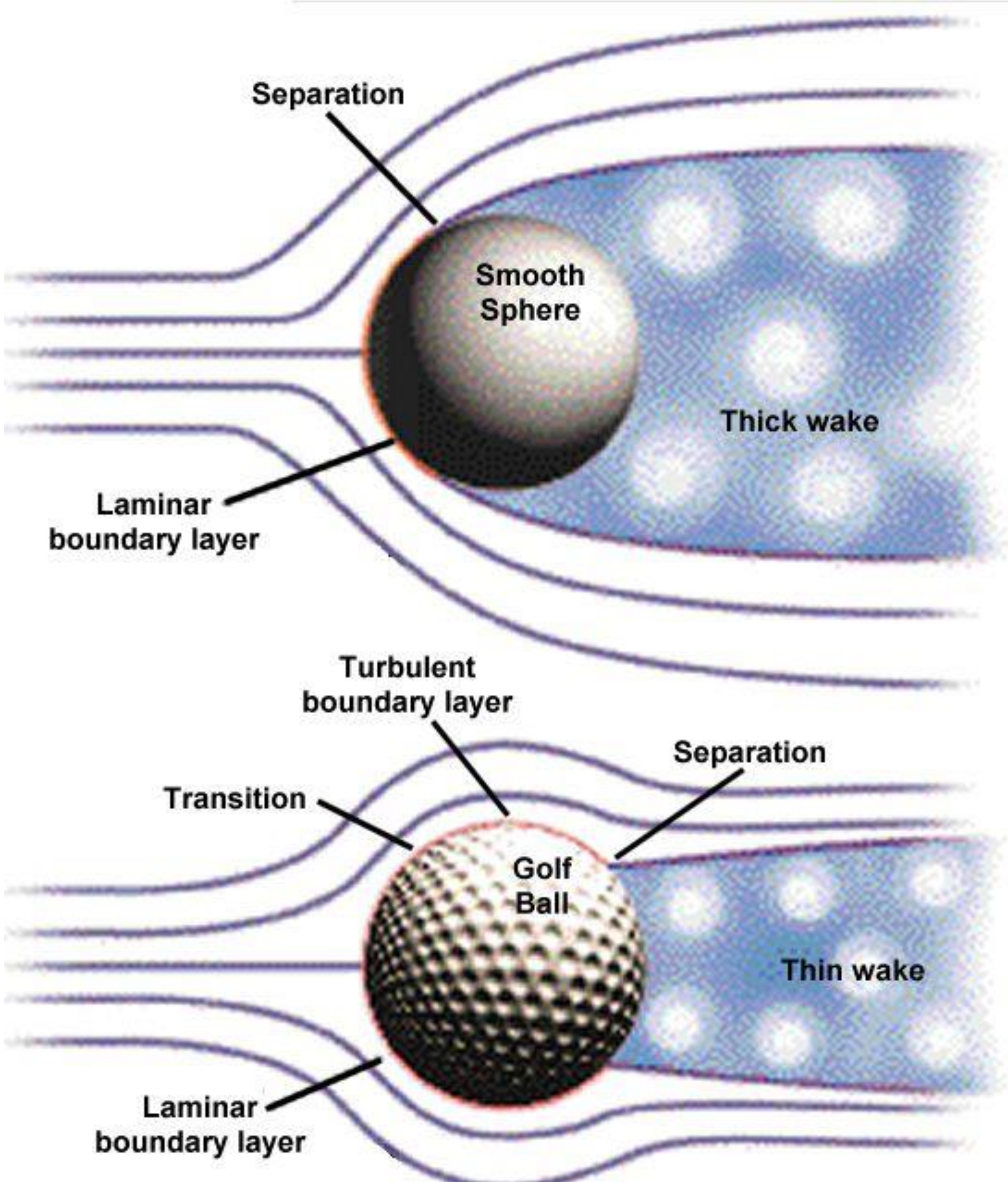
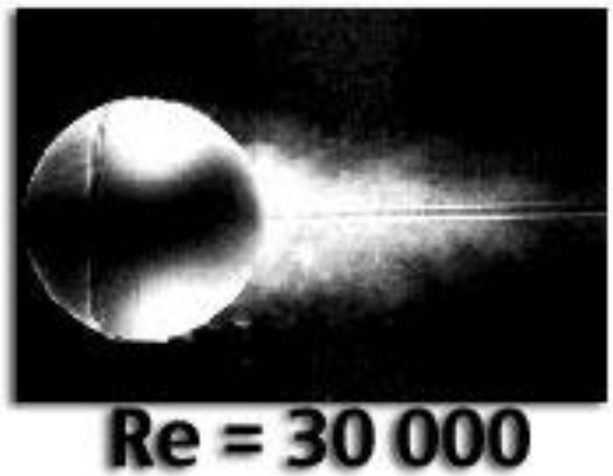


FIGURE 1.14 Pressure on a normal flat plate, flow from left to right.

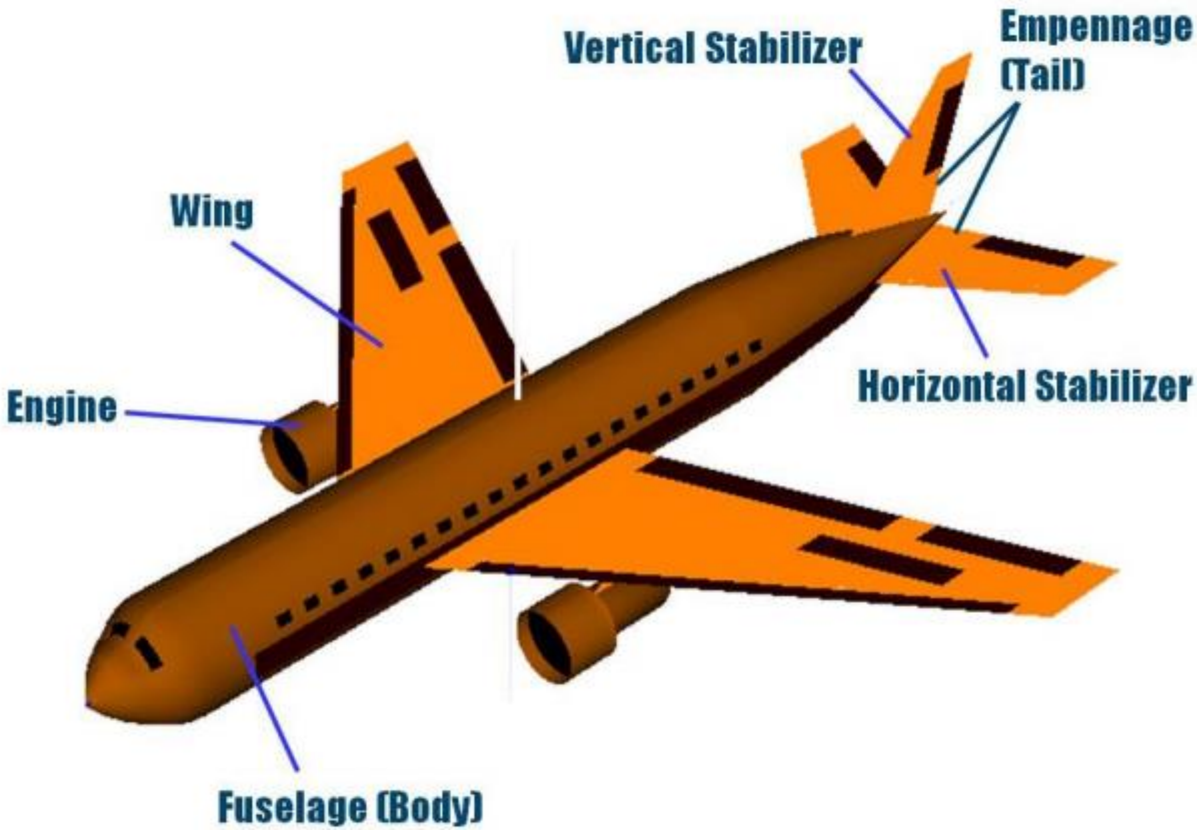

Separation
Smooth Sphere
Thick wake
Laminar boundary layer
Turbulent boundary layer
Separation
Transition
Golf Ball
Thin wake
Laminar boundary layer


Re = 15 000


Re = 30 000


747
BOEING 747-400
mando gomez | mandolux@yahoo.com

# Airplane Parts Definitions

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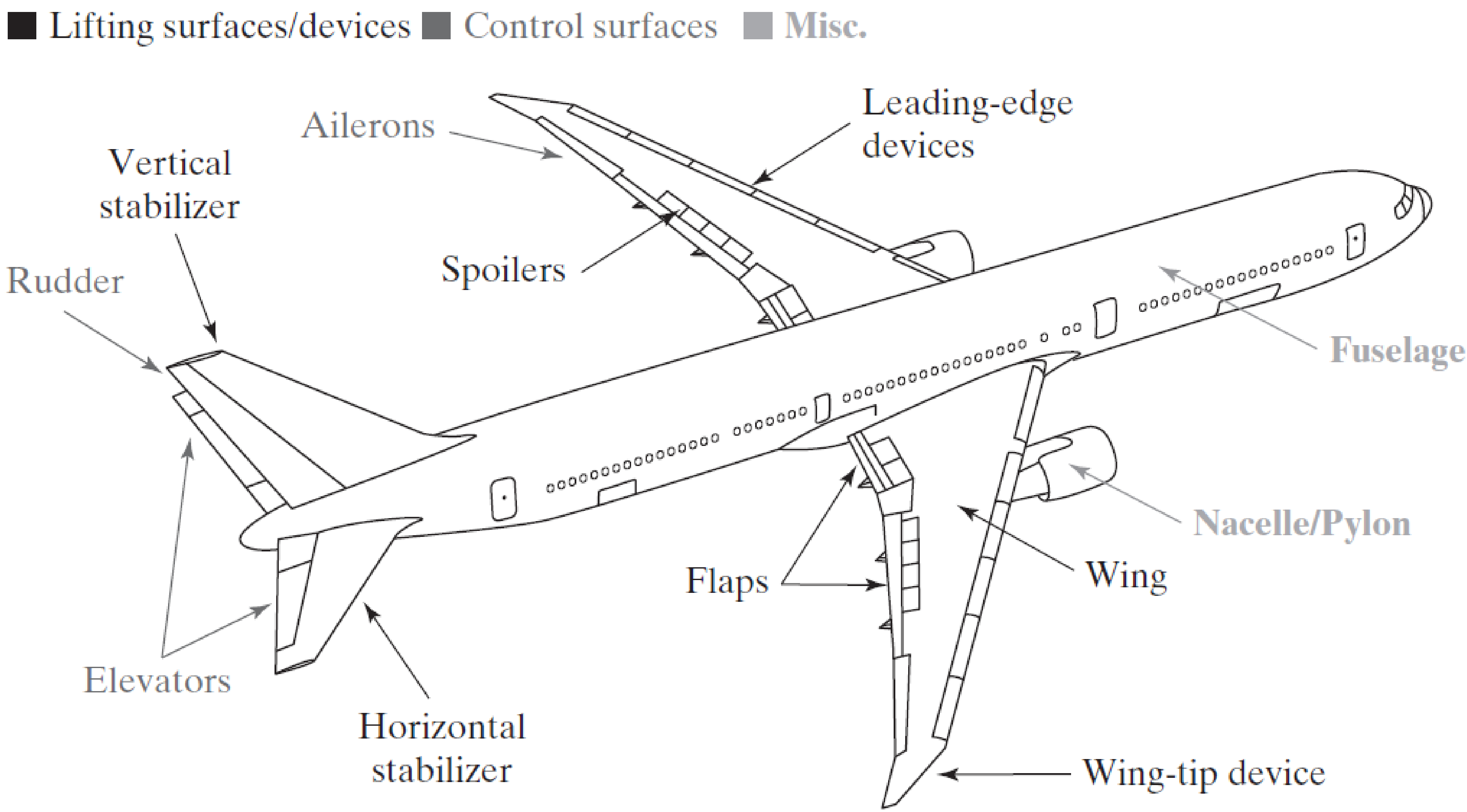



**Figure 1.5** Major components of a modern commercial airliner.

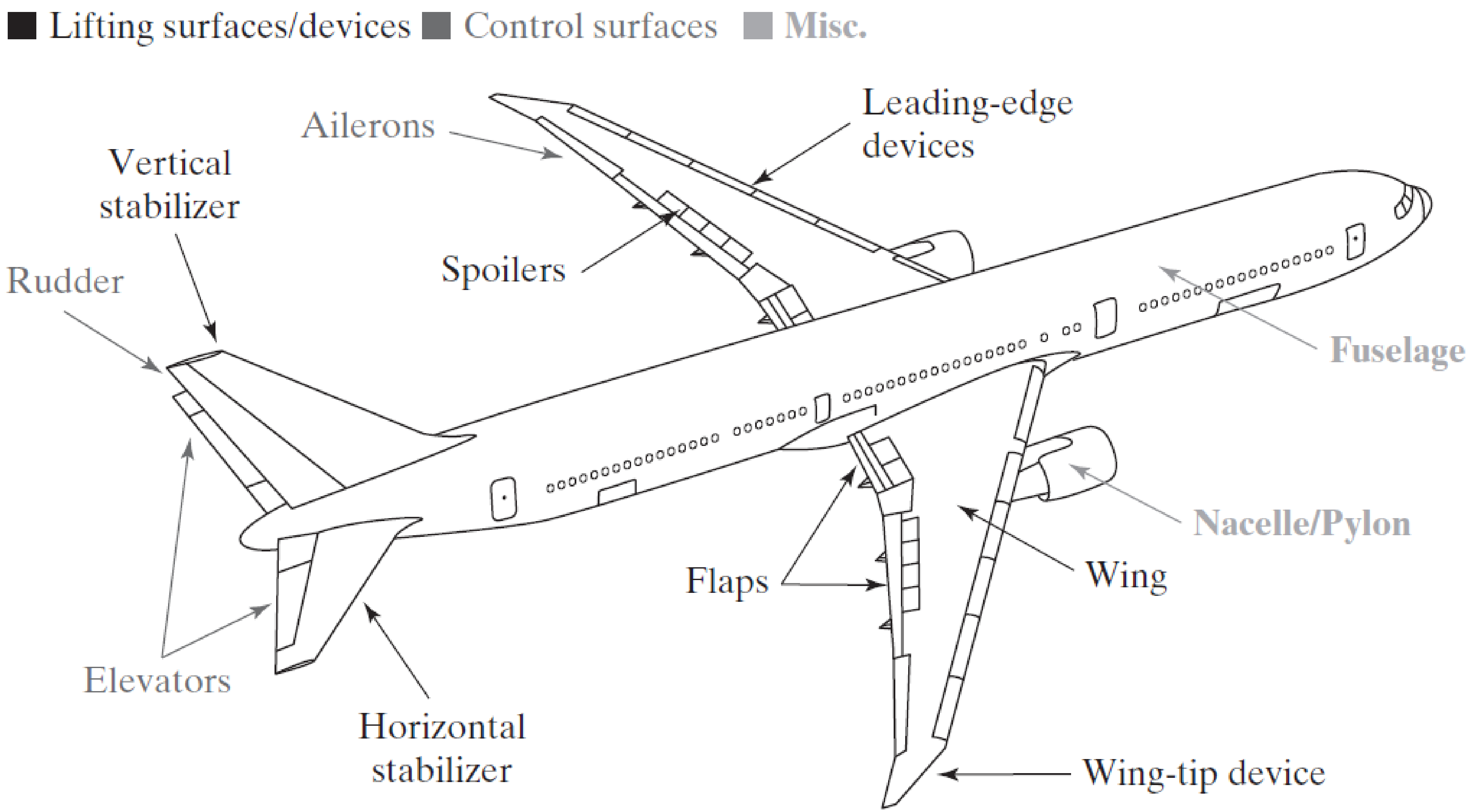



**Figure 1.5** Major components of a modern commercial airliner.

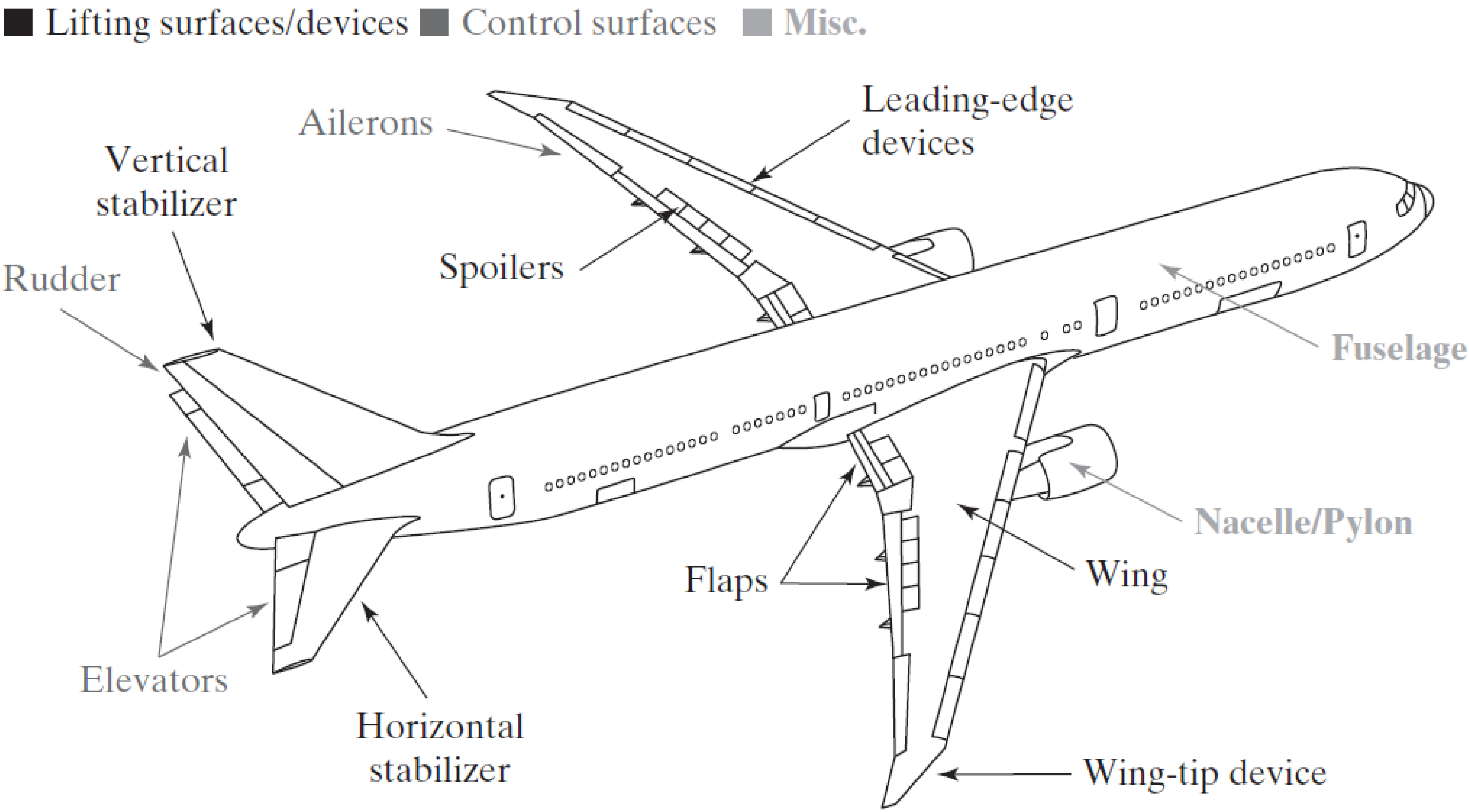
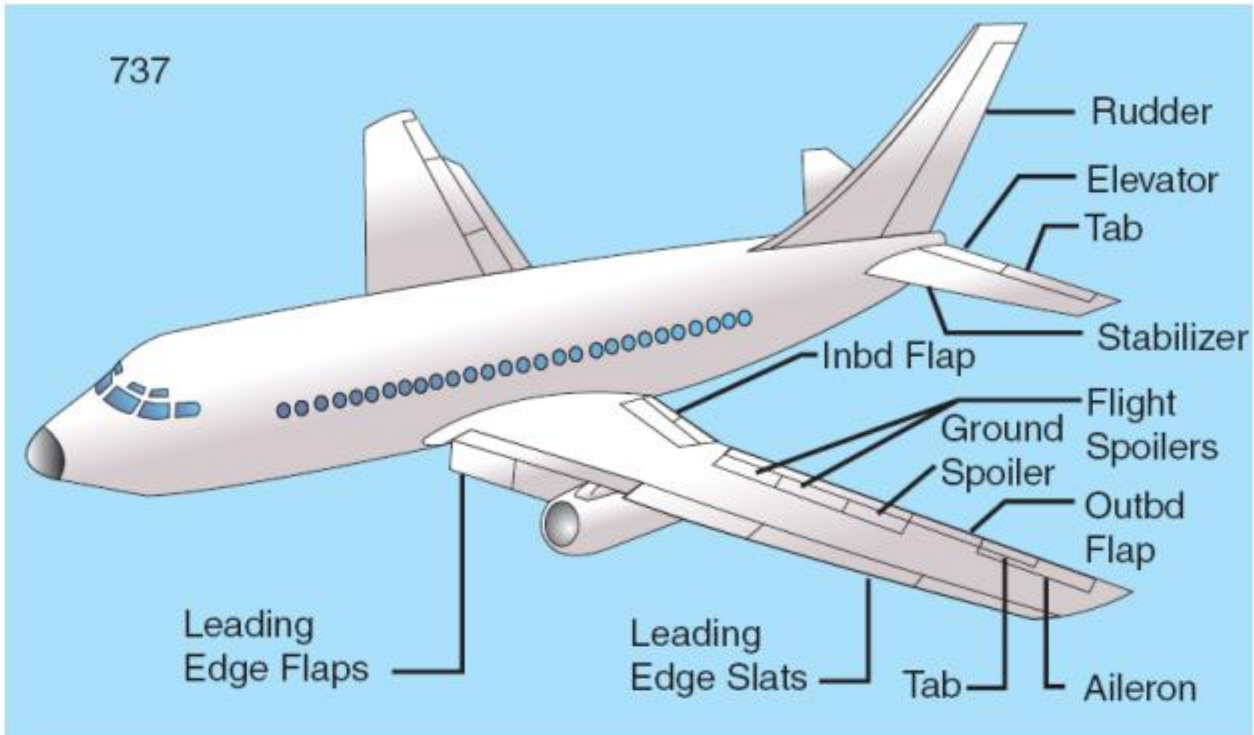



**Figure 1.5** Major components of a modern commercial airliner.

# Airplane Aerodynamics




***Prediction of forces and moments on an airplane moving through air***

## Span

The wingspan is the dimension $b$, the distance between the two wingtips. The distance s=$b/2$ from each tip to the centerline is the wing semi-span.

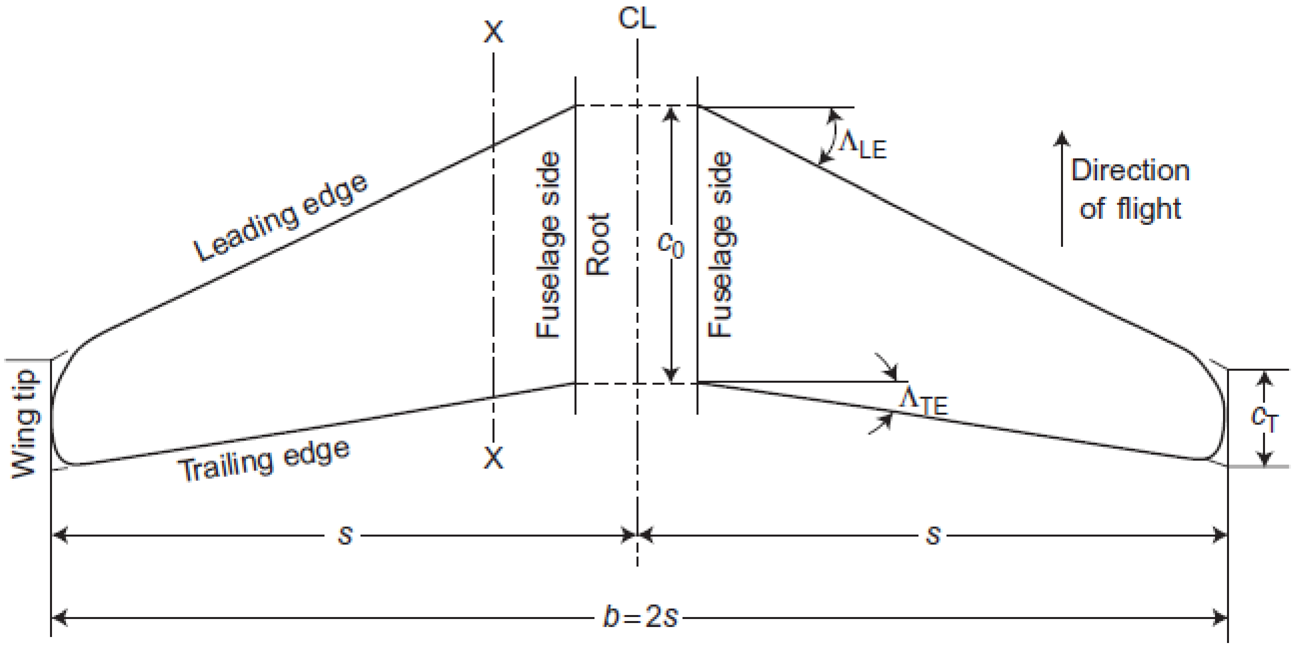



**FIGURE 1.5**

Wing planform geometry.

## Chords

The two lengths $c_T$ and $c_0$ are the tip and root chords, respectively; with the alternative convention, the root chord is the distance between the intersections with the fuselage centerline of the leading and trailing edges produced. The ratio $c_T/c_0$ is the taper ratio. For most wings, $c_T/c_0 < 1$.

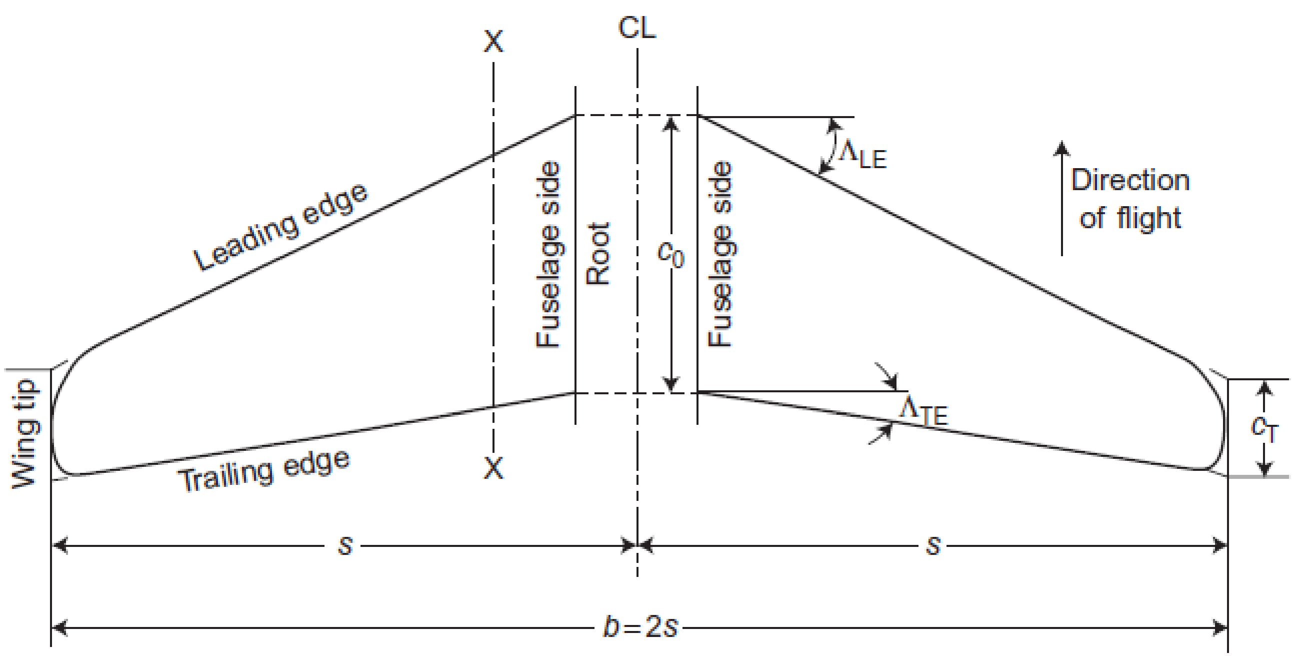



**FIGURE 1.5**

Wing planform geometry.

**Wing Area**

The plan-area of the wing including its continuation in the fuselage is the gross wing area $S_G$. The unqualified term wing area $S$ usually means this gross wing area. The plan-area of the exposed wing (i.e., excluding the continuation in the fuselage) is the net wing area $S_N$.

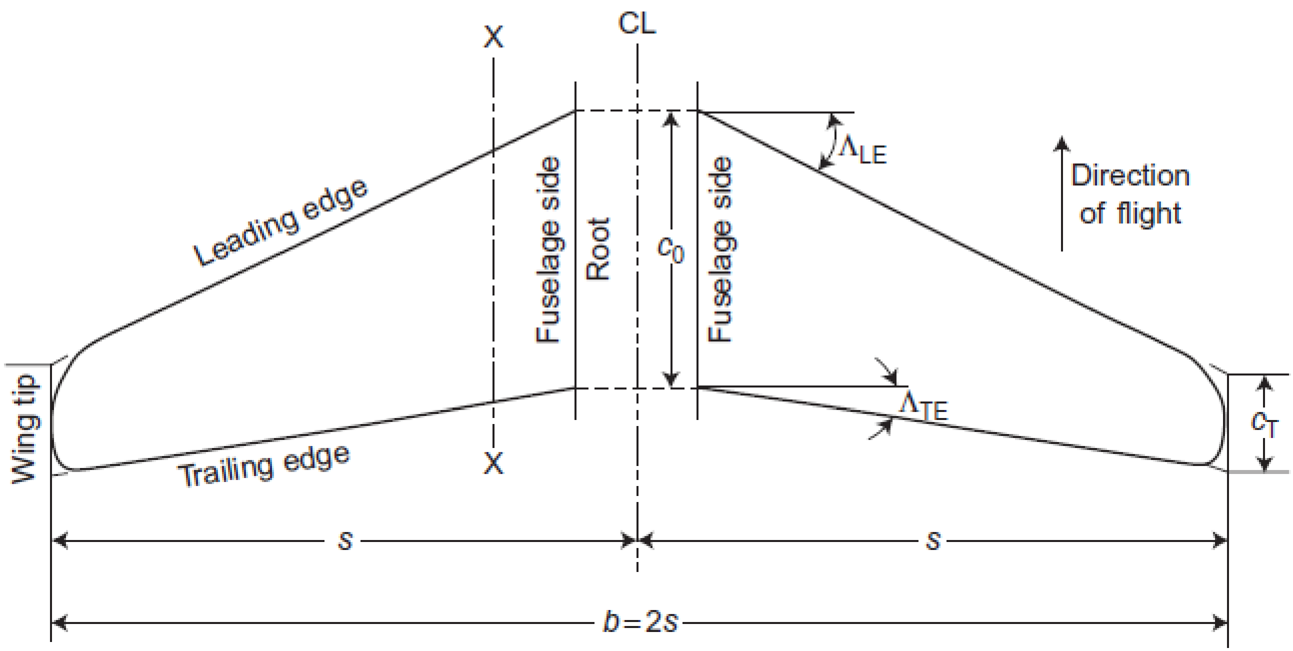



**FIGURE 1.5**

Wing planform geometry.

## Aspect Ratio

Aspect ratio is a measure of the narrowness of the wing planform. It is denoted *AR* and is given by

$$AR = \frac{\text{span}}{\text{area}}$$

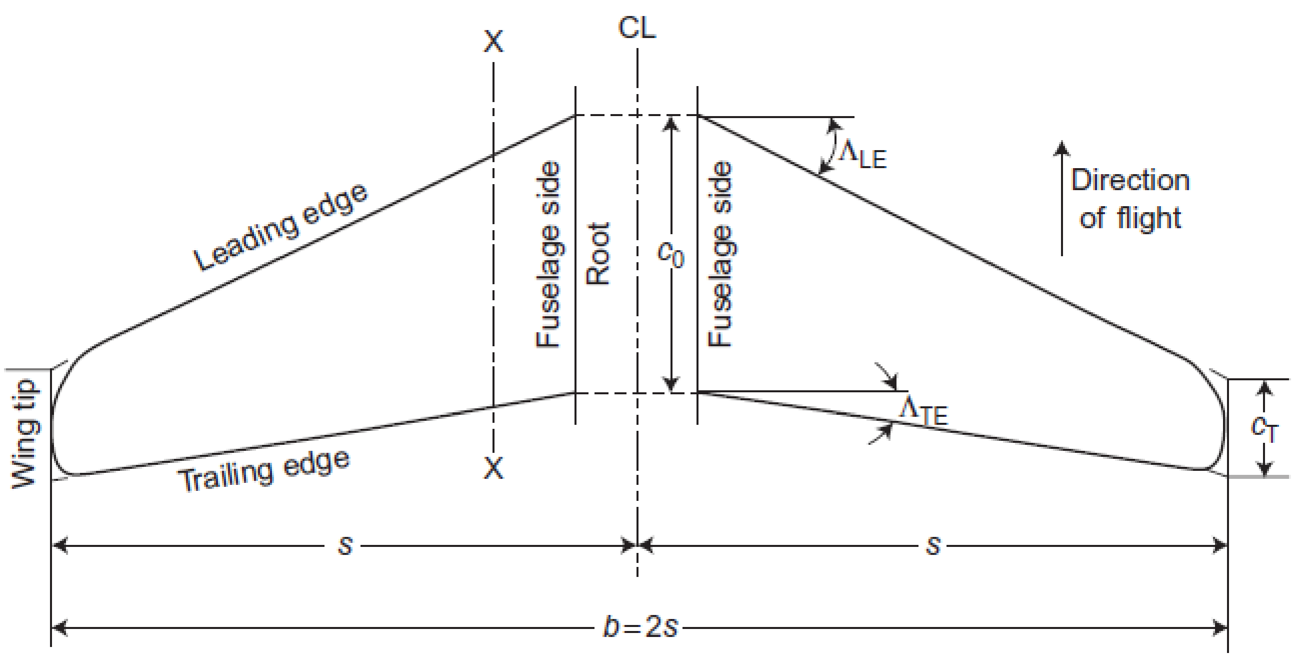



**FIGURE 1.5**

Wing planform geometry.

## Wing Sweep

The sweep angle of a wing is that between a line drawn along the span at a constant fraction of the chord from the leading edge, and a line perpendicular to the centerline.

It is usually denoted $\Lambda$.

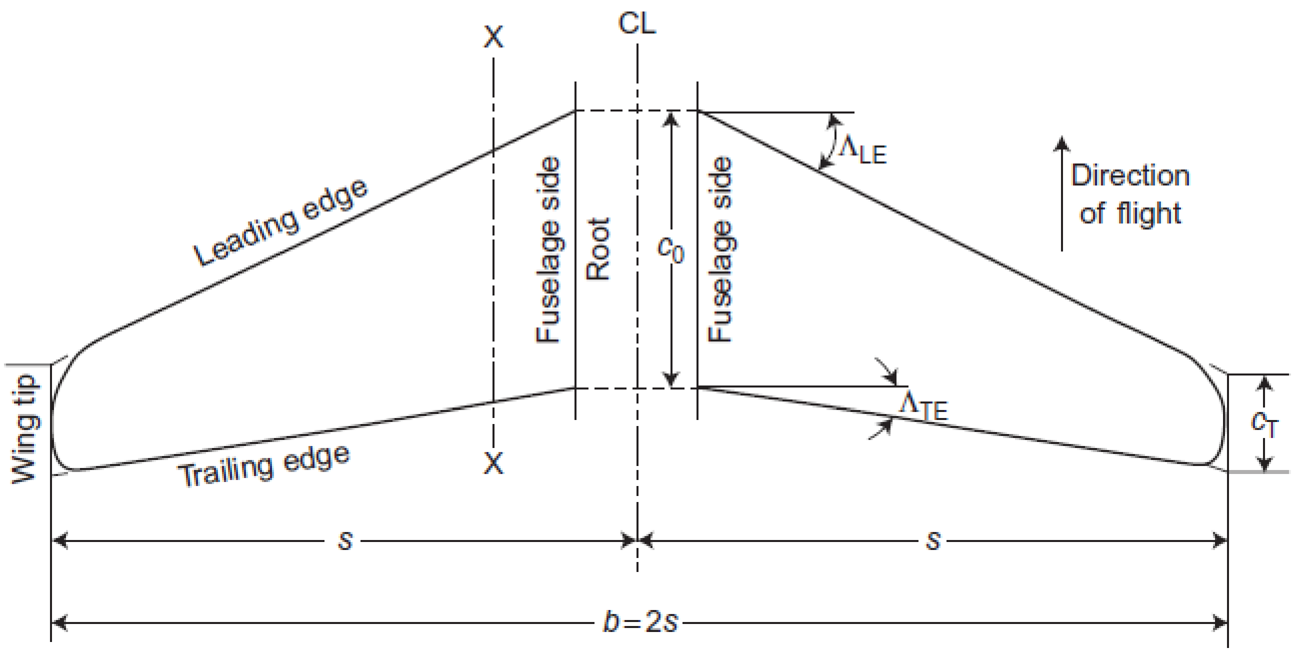



**FIGURE 1.5**

Wing planform geometry.

## Dihedral Angle

If an airplane is viewed from directly ahead, it is seen that the wings are generally not in a single geometric plane but instead inclined to each other at a small angle.

Imagine lines drawn on the wings along the locus of the intersections between the chord lines and the section noses, as in Fig. Then the angle $2\Gamma$ is the dihedral angle of the wings.

If the wings are inclined upward, they are said to have *dihedral*;

if inclined downward, they have *anhedral*