Equilibrium is “TRIM”

... From Newton’s 2\textsuperscript{nd}:
\[ F = ma = 0 \]
\[ L = W \]
\[ T = D \]
787 performance

![Graph showing performance vs. velocity]
Our Heritage …

Sir George Cayley (1773 – 1857): the wing – body – tail configuration separates the lift mechanism from trust mechanism

Otto Lilienthal (1846 – 1896): gliders and related aerodynamics

The Wright Brothers: recognized the need for quality engineering wind tunnel tests for correct aerodynamics warped wings for roll control propellers are wings in rotation

Dates:

Dec. 17, 1903 – Kitty Hawk & Kill Devil Hills, NC … 1st Powered Flight … 12 s, 120 ft
1915 & 1917 – NACA is formed, Langley Aeronautics Labs opened
1908 – the Wright’s convince the world
Oct. 14, 1947 – Bell X1 w/ Chuck Yeager hit Mach 1
Oct. 1958 – NACA becomes NASA
July 20, 1969 – “The Eagle Has Landed” … Neil Armstrong takes first step on moon
April 12, 1981 – Columbia is first shuttle in space

NACA & NASA:
Langley (1917), Ames and Glenn Research Centers  Goddard, Dryden, Stennis
Kennedy, Johnson (1963) and Marshall Flight Centers  JPL, Wallops
Control

- CONVENTIONAL SURFACES (P-40N)

AILERONS - MOVEABLE
PART OF WING TRAILING EDGE
“roll”

ELEVATOR - MOVEABLE
PART OF HORIZONTAL TAIL
“pitch”

RUDDER - MOVEABLE
PART OF VERTICAL TAIL
“yaw”
<table>
<thead>
<tr>
<th></th>
<th>Wright flyer</th>
<th>F-16</th>
<th>747</th>
<th>787</th>
<th>Predator</th>
<th>Condor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Span, ft</strong></td>
<td>40</td>
<td>33</td>
<td>200</td>
<td>200</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td><strong>area, ft^2</strong></td>
<td>500</td>
<td>300</td>
<td>5500</td>
<td>3500</td>
<td>125</td>
<td>1000</td>
</tr>
<tr>
<td><strong>W, lb</strong></td>
<td>750</td>
<td>42,000</td>
<td>840,000</td>
<td>480,000</td>
<td>2250</td>
<td>220</td>
</tr>
<tr>
<td><strong>empty W</strong></td>
<td>600</td>
<td>18,000</td>
<td>400,000</td>
<td>200,000</td>
<td>1600</td>
<td>220</td>
</tr>
<tr>
<td><strong>W/S, lb/ft^2</strong></td>
<td>1.5</td>
<td>60 - 140</td>
<td>70 - 150</td>
<td>70 - 140</td>
<td>13 - 18</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>AR = b^2/S</strong></td>
<td>3.3</td>
<td>3.5</td>
<td>7.3</td>
<td>10</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td><strong>T, lb</strong></td>
<td>P = 12 HP = 7K ft lb/s</td>
<td>17,000</td>
<td>200,000</td>
<td>130,000</td>
<td>P = 85 HP = 50K ft lb/s</td>
<td>P = 1/3 HP = 200 ft lb/s</td>
</tr>
<tr>
<td><strong>T_{AB}, lb</strong></td>
<td>28,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>T/W</strong></td>
<td>&gt; 1</td>
<td>1/4</td>
<td>1/4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>h_{SVC}, ft</strong></td>
<td>30</td>
<td>&gt; 50,000</td>
<td>40,000</td>
<td>40,000</td>
<td>20,000</td>
<td>30</td>
</tr>
<tr>
<td><strong>Range, nm</strong></td>
<td>3</td>
<td>350 - 2000</td>
<td>6700</td>
<td>8100</td>
<td>5000</td>
<td>1</td>
</tr>
<tr>
<td><strong>Velocity, kts</strong></td>
<td>10</td>
<td>1500 (M &gt;2)</td>
<td>600</td>
<td>500</td>
<td>100</td>
<td>10</td>
</tr>
</tbody>
</table>
W/S = “Wing Loading”  
(Force / Area ... ‘pressure’)  

1 atm ~ 2000 lb/ft² ~ 10⁵ N/m²  

50 N/m² ~ 1 lb/ft²  

4.5 N ~ 1 lb  

10 m/s ~ 33 ft/s ~ 22 mi/hr  

“The Simple Science of Flight”  
by Tennekes
AERODYNAMIC FORCES

- A FLOW FIELD
  - IS DEFINED USING A COORDINATE FRAME
  - IS SPECIFIED USING POINT PROPERTIES, including $P$, $\rho$, $T$, AND $V$

  Pressure = $P(x, y, z, t)$
  Velocity = $V(x, y, z, t)$

- PRESSURE ($P$) AND SHEAR ($\tau$) DISTRIBUTIONS, WHICH EXIST ON SURFACES, ARE THE SOURCE OF ALL AERODYNAMIC FORCES (LIFT, DRAG)

\[
P = P(x, y, z, t) \quad \tau = \tau(x, y, z, t)
\]

\[
\text{... these are forces per unit area}
\]

Pressure – normal to surface
Shear – parallel to surface
VELOCITY \& STREAMLINES

AT A FIXED POINT IN A FLUID / GAS …
THE FLOW VELOCITY IS THE VELOCITY OF AN INFINITESIMAL
FLUID ELEMENT AS IT SWEEPS THROUGH THE POINT

VELOCITY IS A VECTOR, HAVING BOTH MAGNITUDE AND DIRECTION

V, P, ρ, and T (velocity, pressure, density, temp) ARE “POINT PROPERTIES” OF THE GAS

EACH REGION OF A GAS IS NOT REQUIRED TO HAVE THE SAME POINT PROPERTIES

A STEADY FLOW IS ONE IN WHICH PROPERTIES DO NOT VARY WITH TIME,
BUT MAY VARY IN SPACE (for example, P (x, y, z, t) \rightarrow P (x, y, z)

“STREAMLINE” – THE (TIME) INVARIANT PATH THAT ALL PARTICLES IN A FLOW
WILL FOLLOW IN A STEADY FLOW. ALL PARTICLES PASSING THROUGH THE
SAME POINT WILL FOLLOW THE SAME STREAMLINE.

WE OBSERVE THAT STREAMLINES CANNOT CROSS PATHS, SINCE THIS SUGGESTS
THE EXISTENCE OF TWO DIFFERENT VELOCITIES AT THE SAME POINT
(… REMEMBER … IT IS A STEADY FLOW).
Pressure

**PRESSURE = NORMAL FORCE PER UNIT AREA EXERTED ON A SURFACE, IT IS DUE TO THE TIME RATE OF CHANGE OF MOMENTUM FOR GAS MOLECULES IMPACTING THAT SURFACE**

- *dA IS THE INCREMENTAL AREA AROUND A POINT ON THE SURFACE*

- *dF IS THE FORCE ON ONE SIDE OF dA DUE TO PRESSURE,*

**SO THE PRESSURE AT THE POINT ON THE SURFACE IS:**

- **UNITS**
  - N/ m² (= Pascal, Pa)
  - LB/FT² (= psf)
  - LB/IN² (= psi)
  - ATM

1 ATM = Standard Pressure at sea level = $p_s$

- $p_s = 2116$ psf
- = 14.7 psi
- = $1.013 \times 10^5$ Pa
WHAT IS THE PRESSURE ON THE INSIDE WALL OF THE FUSELAGE?

WHAT IS THE PRESSURE ON THE OUTSIDE WALL OF THE FUSELAGE?

IF THE FUSELAGE IS IN A VACUUM (OUTER SPACE), AND TEMP IN THE FUSELAGE REMAINS THE SAME), WHAT WILL THE GAUGE READ?

PROPERLY IDENTIFY PRESSURES AS ABS OR GAGE

ALWAYS USE ABSOLUTE PRESSURE IN EQUATIONS

OUTSIDE PRESSURE AT ALTITUDE = 1200 psfa

Aircraft Fuselage

500 psfg
DENSITY / SPECIFIC VOLUME

- **Density** is the mass of a substance per unit volume.

- **Units of Density**
  - kg/m³
  - lb/ft³
  - slug/ft³ = lb·sec²/ft⁴

- **Specific Volume** = volume per unit mass

- **Specific Volume**, \( \nu \), is the reciprocal of \( \rho \)

- Standard Density at sea level
  
  \[ \rho_s = 0.00238 \text{ slug/ft}^3 = 0.00238 \text{ lb·sec}^2/\text{ft}^4 = 1.23 \text{ kg/m}^3 \]
TEMPERATURE SCALES

0 °F = 460 °R
273 °K = 0 °C

°F = 1.8 × °C + 32
°R = 1.8 × °K

Standard Temperature at sea level = T_s = 59 °F = 519 °R = 15 °C = 288 °K
PERFECT GAS

A PERFECT GAS ... A GAS IN WHICH INTERMOLECULAR FORCES ARE NEGLIGIBLE

- **The THERMODYNAMIC STATE EQUATION**

  \[ P = \rho RT \quad \frac{P}{\rho} = \rho \nu = RT \]

  WHERE \( P \equiv \text{PRESSURE}, \rho \equiv \text{DENSITY}, T \equiv \text{TEMPERATURE} \)
  
  \( R \) IS A CONSTANT FOR A SPECIFIC GAS

- **The state equation relates properties at a point, \( T \) is absolute!**

- **FOR AIR**

  \[ R = 287 \frac{J}{\text{Kg}(\circ\text{K})} = 1716 \frac{\text{ft} - \text{lb}}{(\text{slug})(\circ\text{R})} \]
  \[ R = 287 \frac{\text{m}^2}{(\text{sec})^2(\circ\text{K})} = 1716 \frac{\text{ft}^2}{(\text{sec})^2(\circ\text{R})} \]
“STP”
Standard Pressure & Temperature (... air)

Standard Pressure at sea level = $p_s$

$$p_s = 2116 \text{ psf} = 14.7 \text{ psi} = 1.013 \times 10^5 \text{ N/m}^2 \text{ (or, Pa)} = 1 \text{ ATM}$$

Standard Temperature at sea level = $T_s$

$$T_s = 59 \, ^\circ\text{F} = 519 \, ^\circ\text{R} = 15 \, ^\circ\text{C} = 288 \, ^\circ\text{K}$$

and from $P = \rho RT$ where $R = 287 \frac{\text{J}}{(\text{Kg})(^\circ\text{K})} = 1716 \frac{\text{ft-\text{lb}}}{(\text{slug})(^\circ\text{R})}$

Standard Density at sea level = $\rho_s$

$$\rho_s = .00238 \, \text{slug/ft}^3 = .00238 \, \text{lb-sec}^2/\text{ft}^4 = 1.23 \, \text{kg/m}^3$$
Newton’s Law of Universal Gravitation

\[ F = \frac{G M m}{r^2} \]

where

\( F \) = attraction force between 2 bodies
\( M \) = mass of body 1
\( m \) = mass of body 2
\( r \) = distance between centers of bodies
\( G \) = Universal Gravitational Constant
\( = 6.67 \times 10^{-11} \text{ m}^3/\text{kg/sec}^2 \)

The source of “\( g \)”: ( \( \ldots F = ma \) )

\[ \frac{F}{m} = \frac{G M}{r^2} = \frac{G M}{R_{E}^2} = "g" \]

where

\( M = M_E = \text{Mass of Earth} \)
\( r = R_E = \text{mean radius of Earth} \)

leads to

\( g = 32.1 \text{ ft/sec}^2 = 9.81 \text{ m/sec}^2 \)
\( \ldots \text{ at the Earth’s surface} \)
FUNDAMENTALS - UNITS AND DIMENSIONS

- You must get units right! There are no short cuts!
  
  1999, Mars Polar Lander lost during entry into the Martian atmosphere – *miscommunication of units between company and NASA.*

  1982, Air Canada 767 runs out of fuel in flight -
  *pilot thought ground crew meant kg … not lb … of fuel.*

  1980, vibration experiments of NASA’s LDEF are off by a factor of 20 –
  *engineer forgot to convert mass correctly.*

- You must include units on any results, otherwise results are meaningless.

- Use units to confirm an answer that makes sense!

- You must be bilingual & fluent with units –
  a skilled engineer is comfortable with both British and SI units.
We travel to Planet X with a mass-spring calibration kit measured on Earth marked:

“mass = 1 lb”
“stiffness = k = 1.0 lb/ft”

The kit gives a method to relate force, \( F \), and displacement, \( x \), by \( F = k \cdot x \).

The mass is suspended from the spring, and displacement measures force due to gravity.

What is the gravity for Planet X, \( g_X \), if the spring is displaced on Planet X by 2 ft?

In consistent English units, what is the mass of the calibration mass on Planet X?
Units & $F = ma$

- Consistent units obey Newton’s 2nd Law, $F = ma$ … universally … always

- Inconsistent units violate Newton’s 2nd Law, for example, $F = ma/g_c$ is a planet based system.
  On Earth, $g_c = 9.81 \text{ m/sec}^2 = 32.2 \text{ ft/sec}^2$

- Universally, $F = ma$ is a “truth” in any consistent set of units.
  - **English** – lb-ft-sec are defined, mass is the derived unit … the “slug”
    
    $1 \text{ lb} = (1 ?) \times 1 \text{ ft/sec}^2$
    
    $1 \text{ lb} = (1 \text{ lb-sec}^2/\text{ft}) \times 1 \text{ ft/sec}^2$
    
    we identify 1 lb-sec$^2$/ft as 1 slug

  - **Metric** – kg-m-sec are defined, force is the derived unit … the “Newton”
    
    $(1 ?) = 1 \text{ kg} \times 1 \text{ m/sec}^2$
    
    $(1 \text{ kg-m/sec}^2) = 1 \text{ kg} \times 1 \text{ m/sec}^2$
    
    we identify 1 kg-m/sec$^2$ as 1 Newton

We observe that the “slug” and “Newton” are a simple collection of defined units.
Units & $F = ma$

- Inconsistent units violate Newton’s 2\textsuperscript{nd} Law, rather $F = ma/g_c$
  
  … a planet based system On Earth, $g_c = 9.81 \text{ m/sec}^2 = 32.2 \text{ ft/sec}^2$

- Inconsistent units, such as the “lb-mass” and “kg-force” are derived uniquely for Earth.

  - **English – mass is derived**

    $1 \text{ lb} = 1 \text{ lb (mass) x 32.2 ft/sec}^2$
    
    … we note that 1 lb of mass leads to 1 lb of force, on Earth

    $1 \text{ lb} = 1 \text{ slug x 1 ft/sec}^2 = 1 \text{ lb (mass) x 32.2 ft/sec}^2$
    
    … thus, 1 slug = 32.2 lb (mass)

  - **Metric – force is derived**

    $1 \text{ kg (force)} = 1 \text{ kg x 9.81 m/sec}^2$
    
    … we note that 1 kg of mass leads to 1 kg of force, on Earth

    $1 \text{ kg (force)} = 1 \text{ kg x 9.81 m/sec}^2 = 9.81 \text{ N}$
    
    … thus, 1 kg (force) = 9.81 N
Consider these examples:

- **1 pound of force** …
  In British units, mass is \( m = \frac{W}{g} = \frac{(1 \text{ lb})}{(32.2 \text{ ft/s}^2)} = 0.031 \text{ slugs} \)
  … is the mass that exerts 1 lb of force.
  … and some refer to this mass as 1 lb–mass (or 1 lb\(_m\)).

- **1 kilogram of force** …
  In SI, weight \( W = mg = (1 \text{ kg}) (9.81 \text{ m/s}^2) = 9.81 \text{ N} \)
  … is the force exerted by 1 kg of mass.
  … and some refer to this force as 1 kg–force (or 1 kg\(_f\)).

Suggestions:
- Always work in lbs and slugs … or Newtons and kg
- Eliminate the inconsistent unit lb–mass and kg–force
- Properly consider the effect of “g”

- **Eliminate lb used in the mass context with slugs**
  32.2 lb of mass is 1 slug

- **Eliminate kg used in the force context with Newtons**
  1 kg of force is 9.81 Newtons
Units & F = ma

- Established Conversion Factors ... based on defined “standards”
  - 2.2 lb = 1 kg  (note, this is mass ... and force too, on Earth of course)
  - 3.28 ft = 1 m

- Derived Conversions
  - 1 N = 1 kg x 1 m/sec² = 2.2 lb x 3.28 ft/sec² = 7.22 lb ft/sec²
    (does not make ‘unit’ sense)

  … realization! we must convert to make complete unit sense

  1 N = 2.2 lb x 3.28 lb ft/sec²
  = 2.2 lb / 32.2 lb/slug x 3.28 ft/sec²
  = .224 slug-ft/sec²
  = .224 lb/sec²
  = .224 lb-sec²/ft x ft/sec²
  = .224 lb
  … a force, of course

thus, 1 N = .224 lb ... Units have worked for us
BUOYANCY

- Millennia ago, Archimedes proved that an upward buoyant force \( B \) exists on a body that is equal to the weight of the fluid displaced by the body volume. (\( B \) is not the weight of the body)

- The shape of the body does not matter, and the upward force is equal to the summation of all forces acting on the body due to normal pressures acting on the body.