Computers and Aviation

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Stanford University

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Objective

• To trace the parallel development of computing and flight over the last 300 years, culminating in a fusion of engineering, mathematics and computing in modern aviation.

Fusion of Flight Experiments, Mathematics, and Computing:
History of Aviation

Leonardo da Vinci
• laid out various concepts of flying machines
George Cayley (1799 – 1850’s)
- identified the four aerodynamic forces
- set forth concept of the modern airplane
- built a successful human-carrying glider

Otto Lilienthal
- was an important source of inspiration and information for practical flying machine

Samuel P. Langley (1896)
- built powered, heavier-than-air machine that had achieved sustained flight (no pilot)
**Orville and Wilbur Wright (1903)**
- completed the first powered, controlled flight at Kitty Hawk, North Carolina.

**DC 3 Design Team (1935):**
- Dutch Kindelberger
- Lee Atwood
- Jack Northrop
- Arthur Raymond
- Assisted by Caltech

**Spitfire (1936)**
- designed by R.J. Mitchell
- Beverley Shenstone (Wing)
Frank Whittle
- patent (1930)
- built first engine (1937)

First flight in Gloster E.28/39 (1941)

Hans Von Ohain
- was the first to power an all-jet aircraft (1938)

Heinkel He 178
ME 262 (1941)

Boeing 747 (1969)
- designed led by Joe Sutter

SR 71 (1964)
- design led by Kelly Johnson and Ben Rich

Airbus 380 (2005)
History of Computers

Pascal's Pascaline (1642)

Leibniz's Stepped Reckoner (1640's)

Babbage's Difference Engine and Analytic Engine (1822)

Jacquard's Loom (1801)
**Alan Turing** (1912-1954)
- Turing Machine

**John von Neumann** (1944)
- von Neumann architecture

**Mark I** (1944)
- first programmable digital computer

**ACE** (1945)
- Automatic Computing Engine

**ENIAC** (1946)
- Electronic Numerical Integrator And Computer
# Supercomputers Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Model</th>
<th>MFLOPS</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964</td>
<td>CDC 6600</td>
<td>3 MFLOPS</td>
<td>AEC-Lawrence Livermore National Laboratory, California, USA</td>
</tr>
<tr>
<td>1969</td>
<td>CDC 7600</td>
<td>36 MFLOPS</td>
<td></td>
</tr>
<tr>
<td>1974</td>
<td>CDC STAR-100</td>
<td>100 MFLOPS</td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td>Burroughs ILLIAC IV</td>
<td>150 MFLOPS</td>
<td>NASA Ames Research Center, California, USA</td>
</tr>
<tr>
<td>1976</td>
<td>Cray-1</td>
<td>250 MFLOPS</td>
<td>Energy Research and Development Administration (ERDA)</td>
</tr>
<tr>
<td>1981</td>
<td>CDC Cyber 205</td>
<td>400 MFLOPS</td>
<td>(~40 systems worldwide)</td>
</tr>
<tr>
<td>1983</td>
<td>Cray X-MP/4</td>
<td>941 MFLOPS</td>
<td>U.S. Department of Energy (DoE)</td>
</tr>
<tr>
<td>1984</td>
<td>M-13</td>
<td>2.4 GFLOPS</td>
<td>Scientific Research Institute of Computer Complexes, Moscow, USSR</td>
</tr>
<tr>
<td>1985</td>
<td>Cray-2/8</td>
<td>3.9 GFLOPS</td>
<td>DoE-Lawrence Livermore National Laboratory, California, USA</td>
</tr>
<tr>
<td>1989</td>
<td>ETA10-G/8</td>
<td>10.3 GFLOPS</td>
<td>Florida State University, Florida, USA</td>
</tr>
<tr>
<td>1990</td>
<td>NEC SX-3/44R</td>
<td>23.2 GFLOPS</td>
<td>NEC Fuchu Plant, Fuchū, Tokyo, Japan</td>
</tr>
<tr>
<td>1993</td>
<td>Thinking Machines CM-5/1024</td>
<td>59.7 GFLOPS</td>
<td>DoE-Los Alamos National Laboratory; National Security Agency</td>
</tr>
<tr>
<td>1993</td>
<td>Fujitsu Numerical Wind Tunnel</td>
<td>124.50 GFLOPS</td>
<td>National Aerospace Laboratory, Tokyo, Japan</td>
</tr>
<tr>
<td>1994</td>
<td>Fujitsu Numerical Wind Tunnel</td>
<td>170.40 GFLOPS</td>
<td>National Aerospace Laboratory, Tokyo, Japan</td>
</tr>
<tr>
<td>1996</td>
<td>Hitachi SR2201/1024</td>
<td>220.4 GFLOPS</td>
<td>University of Tokyo, Japan</td>
</tr>
<tr>
<td>1996</td>
<td>Hitachi/Tsukuba CP-PACS/2048</td>
<td>368.2 GFLOPS</td>
<td>Center for Computational Physics, University of Tsukuba, Tsukuba, Japan</td>
</tr>
<tr>
<td>1997</td>
<td>Intel ASCI Red/9152</td>
<td>1.338 TFLOPS</td>
<td>DoE-Sandia National Laboratories, New Mexico, USA</td>
</tr>
<tr>
<td>1999</td>
<td>Intel ASCI Red/9632</td>
<td>2.3796 TFLOPS</td>
<td>USA</td>
</tr>
</tbody>
</table>
## Supercomputers Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>System</th>
<th>Performance</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>IBM ASCI White</td>
<td>7.226 TFLOPS</td>
<td>DoE-Lawrence Livermore National Laboratory, California, USA</td>
</tr>
<tr>
<td>2002</td>
<td>NEC Earth Simulator</td>
<td>35.86 TFLOPS</td>
<td>Earth Simulator Center, Yokohama, Japan</td>
</tr>
<tr>
<td>2004</td>
<td>IBM Blue Gene/L</td>
<td>70.72 TFLOPS</td>
<td>DoE/IBM Rochester, Minnesota, USA</td>
</tr>
<tr>
<td>2005</td>
<td>IBM Roadrunner</td>
<td>136.8 TFLOPS</td>
<td>DoE/U.S. National Nuclear Security Administration, Lawrence Livermore National Laboratory, California, USA</td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td>280.6 TFLOPS</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td>478.2 TFLOPS</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>IBM Roadrunner</td>
<td>1.026 PFLOPS</td>
<td>DoE-Los Alamos National Laboratory, New Mexico, USA</td>
</tr>
<tr>
<td>2009</td>
<td>Cray Jaguar</td>
<td>1.105 PFLOPS</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Cray Jaguar</td>
<td>1.759 PFLOPS</td>
<td>DoE-Oak Ridge National Laboratory, Tennessee, USA</td>
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</tbody>
</table>

- **2012**: Sequoia, 20 PFLOPS, IBM

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**NEC Earth Simulator**

**IBM Blue Gene**
Personal Computers

Xerox Alto 1973
Altair 1975
IBM PC 1981
Apple II 1977
PC Laptop and MacBook (2000’s)
## Microprocessor Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Name</th>
<th>Developer</th>
<th>Mfg. Process</th>
<th>Transistors</th>
<th>Clock</th>
<th>Bits</th>
<th>Core</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>4004</td>
<td>Intel</td>
<td>10 µm</td>
<td>2,250</td>
<td>108 kHz</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>1972</td>
<td>8008</td>
<td>Intel</td>
<td>10 µm</td>
<td>3,500</td>
<td>200 kHz</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>1974</td>
<td>6800</td>
<td>Motorola</td>
<td>-</td>
<td>4,100</td>
<td>2 MHz</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>1978</td>
<td>8086</td>
<td>Intel</td>
<td>3 µm</td>
<td>29,000</td>
<td>4.77 MHz</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>1979</td>
<td>68000</td>
<td>Motorola</td>
<td>4 µm</td>
<td>68,000</td>
<td>8 MHz</td>
<td>16/32</td>
<td>1</td>
</tr>
<tr>
<td>1982</td>
<td>80286</td>
<td>Intel</td>
<td>1.5 µm</td>
<td>134,000</td>
<td>6 MHz</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>1985</td>
<td>80386</td>
<td>Intel</td>
<td>1.5 µm</td>
<td>275,000</td>
<td>16 MHz</td>
<td>32</td>
<td>1</td>
</tr>
<tr>
<td>1989</td>
<td>80486</td>
<td>Intel</td>
<td>1 µm</td>
<td>1.2 M</td>
<td>25 MHz</td>
<td>32</td>
<td>1</td>
</tr>
<tr>
<td>1990</td>
<td>Power1</td>
<td>IBM</td>
<td>1 µm</td>
<td>6.9 M</td>
<td>20-30 MHz</td>
<td>32</td>
<td>1</td>
</tr>
<tr>
<td>1993</td>
<td>Pentium</td>
<td>Intel</td>
<td>0.8 µm</td>
<td>3.1 M</td>
<td>66 MHz</td>
<td>32</td>
<td>1</td>
</tr>
<tr>
<td>1997</td>
<td>Pentium II</td>
<td>Intel</td>
<td>0.25 µm</td>
<td>7.5 M</td>
<td>300 MHz</td>
<td>32</td>
<td>1</td>
</tr>
<tr>
<td>1999</td>
<td>Pentium III</td>
<td>Intel</td>
<td>0.18 µm</td>
<td>9.5 M</td>
<td>500 MHz</td>
<td>32</td>
<td>1</td>
</tr>
<tr>
<td>2000</td>
<td>Pentium IV</td>
<td>Intel</td>
<td>0.18 µm</td>
<td>42 M</td>
<td>1.5 GHz</td>
<td>32</td>
<td>1</td>
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<tr>
<td>2001</td>
<td>Power4</td>
<td>IBM</td>
<td>90 nm</td>
<td>174 M</td>
<td>1.1-1.4 GHz</td>
<td>64</td>
<td>1</td>
</tr>
<tr>
<td>2003</td>
<td>Opteron</td>
<td>AMD</td>
<td>130 nm</td>
<td>106 M</td>
<td>1.4-2.4 GHz</td>
<td>32/64</td>
<td>1</td>
</tr>
<tr>
<td>2006</td>
<td>Core Duo</td>
<td>Intel</td>
<td>65 nm</td>
<td>152 M</td>
<td>2 GHz</td>
<td>64</td>
<td>2</td>
</tr>
<tr>
<td>2006</td>
<td>Quad Core Xeon</td>
<td>Intel</td>
<td>65 nm</td>
<td>291 M</td>
<td>3 GHz</td>
<td>64</td>
<td>4</td>
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<tr>
<td>2007</td>
<td>Core 2 Quad</td>
<td>Intel</td>
<td>65 nm</td>
<td>582 M</td>
<td>2.4 GHz</td>
<td>64</td>
<td>4</td>
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<tr>
<td>2008</td>
<td>Core i7</td>
<td>Intel</td>
<td>45 nm</td>
<td>774 M</td>
<td>2.933 GHz</td>
<td>64</td>
<td>4</td>
</tr>
<tr>
<td>2008</td>
<td>Six Core Xeon</td>
<td>Intel</td>
<td>45 nm</td>
<td>1,900 M</td>
<td>2.667 GHz</td>
<td>64</td>
<td>6</td>
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</tbody>
</table>
Microprocessor Progress – Intel

Gordon Moore
Intel Co-Founder

Robert Noyce
Intel Co-Founder

Marcian E. “Ted” Hoff
Credited to be the inventor of the 1st microprocessor—Intel 4004

- Weight vs Capability
- The dramatic increase in computational capability is accompanied by equally dramatic decrease in the weight and cost of the computer.

- While computers were getting more powerful, enabling aerodynamic and structural calculations of complete aircraft, and simulations of the evolution of the universe, they were also getting smaller, enabling airborne computers with onboard software and fly-by-wire.

Impact of Computer Evolution With Constant Performance

<table>
<thead>
<tr>
<th>Year</th>
<th>Computer</th>
<th>Weight</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>Convex</td>
<td>1000 lbs</td>
<td>$600K</td>
</tr>
<tr>
<td>2000</td>
<td>Sony</td>
<td>3.75 lbs</td>
<td>$3K</td>
</tr>
<tr>
<td>2015</td>
<td>Raspberry Pi B+</td>
<td>0.2 oz</td>
<td>$60</td>
</tr>
</tbody>
</table>
• The Modern Role of Computing in Aviation
Major Impact in Multiple Ways

1. Computational Analysis for Structural and Aerodynamic Design
2. Computer Aided Design (CAD) – Paperless Airplane
3. Computational Control and Navigation – Fly-by-Wire

Major Milestones

1. First airplane with wing designed by CFD – Canadair Challenger (1977)
2. First commercial aircraft with fly-by-wire – Airbus A320 (1982)
3. First commercial aircraft with digital design – Boeing B777 (1994)
Emergence of Computational Structural Mechanics (CSM)  
1960 - 1980

* Now embodied in commercial software such as MSC NASTRAN & ANSYS
History of Finite Element Analysis (FEA)

Timeline: Milestones in FEA and meshless basis function development

1779  
Lagrange polynomials

1864  
Hermite polynomials

1943  
Linear triangle

1960  
Clough coins the name “finite elements”

1961  
Bilinear quadrilateral

1962  
Linear tetrahedron

1965–1968  
$C^1$-continuous triangles and quadrilaterals

1966  
Isoparametric elements

1968–1971  
Variable-number-of-nodes elements

1977–1986  
$H(\text{div})$, $H(\text{curl})$, and $H(\text{div}) \oplus H(\text{curl})$ elements

1992–1996  
Meshless methods
Mathematical Theory of Fluid Dynamics
Three Main Eras

- **1680-1920** Analytical linear theories
  - Newton
  - Bernoulli
  - Euler
  - Laplace
  - Kutta
  - Prandtl
  - Glauert

- **1920-1960** Analytical asymptotic and nonlinear theories
  - von Karman
  - Taylor
  - Lighthill

- **1960-Present** Computational Fluid Dynamics
  - fully-nonlinear calculations
1680-1920
Analytical linear theories
• Hydrodynamics
• Bernoulli's Principle
  ❖ in an inviscid flow an increase in the fluid speed occurs with a decrease in pressure or potential energy

\[ \frac{v^2}{2} + gz + \frac{p}{\rho} = \text{constant} \]

▶ Euler Equations
  ❖ govern flow of fluid with no viscosity
  ❖ directly represent conservation of mass, momentum, and energy

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \]

\[ \frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \otimes (\rho \mathbf{u})) + \nabla p = 0 \]

\[ \frac{\partial E}{\partial t} + \nabla \cdot (\mathbf{u}(E + p)) = 0, \]
• Laplace Equation
  - describes behavior of fluid potential
    \[
    \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0.
    \]

  ➤ Kelvin’s Theorem
  - Circulation, \( \Gamma = \int V \cdot dS \), remains constant in Inviscid flow
  - Hence inviscid incompressible flow is generally irrotational \( \nabla \times V = 0 \)
  - So one can set \( V = \nabla \varphi \) and \( \nabla \cdot V = 0 \)

  ➤ d’Alembert’s Paradox
  - Zero drag in frictionless flow
• Navier-Stokes Equations
  • govern motion of fluid
  • arise from applying Newton's second law to fluid motion
  • assume that the fluid stress is proportional to the gradient of velocity, plus a pressure term

• Incompressible Navier-Stokes Equations

• Millennium Prize Problem
  • Navier–Stokes existence and smoothness
  • theoretical understanding of the solutions to these equations is incomplete
  • solutions of the Navier–Stokes equations often include turbulence, which remains one of the greatest unsolved problems in physics

Claude-Louis Navier
(1785-1836)

George Gabriel Stokes
(1819-1903)
Ludwig Boltzmann  
(1844-1906)

William Rankine  
(1820-1872) &  
Pierre-Henri Hugoniot  
(1851-1887)

Boltzmann Equation

- For probability density in velocity and position space

\[
\frac{\partial f}{\partial t} + v \frac{\partial f}{\partial x} + \frac{F}{m} \frac{\partial f}{\partial v} = \frac{\partial f}{\partial t} \bigg|_{\text{collision}}
\]

Rankine-Hugoniot shock relation

\[
\frac{\rho_2}{\rho_1} = \frac{\frac{p_2}{p_1} (\gamma + 1) + (\gamma - 1)}{\gamma + 1} = \frac{u_1}{u_2}
\]

\[
\frac{p_2}{p_1} = \frac{\frac{p_2}{p_1} (\gamma + 1) - (\gamma - 1)}{\gamma + 1} - \frac{\rho_2}{\rho_1} (\gamma - 1).
\]
Reynolds Number

\[ \text{Re} = \frac{\rho VL}{\mu} = \frac{VL}{\nu} = \frac{QL}{\nu A} \]

- Re No. can be understood as the ratio of the inertial forces to the viscous forces
- Re No. sets the smallest scales of turbulent motion
- the largest eddies are dictated by the flow geometry
- the smallest scales are dictated by the viscosity

[Diagram showing flow development with stages labeled 1 to 6:]

1. stable laminar flow
2. unstable Tollmien-Schlichting waves
3. 3-dimensional waves and \( \Lambda \)-vortices
4. Break down of \( \Lambda \)-vortices
5. Formation of turbulent spots
6. fully turbulent flow
Ernst Mach
(1838-1916)

- **Mach Number** $M = \frac{v}{a}$
  - the speed, $v$, of an object moving through a fluid substance divided by the speed of sound $a$.

  - Shock waves appear in transonic and supersonic flow
Frederick Lanchester  •  Circulation Theory of Lift

Martin Wilhelm Kutta
(1867-1944) &
Nikolai Joukowski
(1847-1921)

Kutta-Joukowski Theorem \[ L = \rho_\infty V_\infty \Gamma_\infty, \]
relates the lift generated by a right cylinder to the speed of the cylinder through the fluid, the density of the fluid, and the circulation.
Ludwig Prandtl (1875-1953)

- Lifting Line Theory

- Prandtl number

\[ \text{Pr} = \frac{\nu}{\alpha} = \frac{\text{viscous diffusion rate}}{\text{thermal diffusion rate}} = \frac{c_p \mu}{k} \]

- Boundary Layer Theory

- Oblique Expansion Shock Wave (Prandtl-Glauert Correction)
1920-1960
Analytical asymptotic and nonlinear theories
G. I. Taylor  
(1886-1975)

Theodore von Kármán  
(1881-1963)

• Shock Wave Structure

Von Kármán Vortex Street
• Thin Airfoil Theory

\[ c_L = c_{L_0} + 2\pi \alpha \]

- Swept Wing Theory
Andrey Kolmogorov (1903-1987)

- Turbulence
- Kolmogorov microscale
  \( \text{Smallest scale} \sim \frac{1}{(Re)^{3/4}} \)

Richard Whitcomb (1921-2009)

- Supercritical Airfoil
- Winglet
- Transonic Area Rule ("Coke Bottle")
Emergence of CFD 1965–2005

- In 1960, the underlying principles of fluid dynamics and the formulation of the governing equations (potential flow, Euler, RANS) were well established.

- The new element was the emergence of powerful enough computers to make numerical solution possible – to carry this out required new algorithms.

- The emergence of CFD in the 1965 – 2005 period depended on a combination of advances in computer power and algorithms.
Basic Principle of Finite Volume Schemes for CFD

① Divide the domain into a grid of computational cells

② Apply the conservation laws of mass, momentum and energy in integral form separately for each cell

③ 5N equations for 5N unknowns on a grid of N cells
Examples: Northrop YF23, A320 and SST

Euler Solutions around 1985-1990
Examples: Unstructured TAU Code

Tool for complex configurations
• hybrid meshes, cell vertex / cell centered
• high-level turbulence & transition models (RSM, DES, linear stability methods)
• state-of-the-art algorithms (JST, multigrid,...)
• local mesh adaptation
• chimera technique
• fluid / structure coupling
• continuous / discrete adjoint
• extensions to hypersonic flows
CFD Contributions to A380 & B787

Airbus A380

- Frequent use
- Moderate use
- Growing use

Boeing 787

- Wind-Tunnel Corrections
- Vertical Tail and Aft Body Design
- High-Speed Wing Design
- Vortex Generators
- Flutter
- Interior Air Quality
- Cab Design

- Planform Design
- Aeroelastics
- High-Speed Wing Design
- Flutter
- Air-Data System Location

- APU Outlet Design
- APU Inlet and Ducting
- APU and Propulsion Fire Suppression
- Design for Stability & Control
- Engine/Bay Thermal Analysis
- Design for FOD Prevention

- Shell Fairing
- Control-Surface Failure Analysis
- Icing
- Inlet Design
- Inlet Certification

- APU Inlet Design
- Exhaust System Design
- Thrust-Reverser Design
- ECS Inlet Design
- Engine/Frame Integration
- Nacelle Design

- Control-Surface Design
- Flutter
- Inlet Design
- Inlet Certification

- Powerplant Integration
- Nacelle Design
- Engine Core Compartiment
- Thrust Reverser Design
- Wind Tip Design

- Cabin Ventilation
- Fuselage Design
- Cockpit Avionics Ventilation
- Engine Core Compartiment
- Thrust Reverser Design

- Cabin Noise
- Low Speed Wing Design
- Ice Prediction
- High Speed Wing Design
- Spoiler Control Surfaces

- Fuel System Design
- APU Inlet/Outlet Design
- External Noise Sources
- Handling Quality Data
- Static Deformation
Airplane Design Considerations
Overall Airplane Design Process

Conceptual Design
- 15-30 engineers
- 1.5 years
- $6-12 million

Preliminary Design
- 100-300 engineers
- 2.5 years
- $60-120 million

Final Design
- 6000 engineers
- 5 years
- $3-12 billion

Defines Mission
Preliminary sizing
Weight, performance
Airplane Industry Cash Flow

Economic Projection (Jumbo Jet)

- **Conceptual Design**: Decisions here decide final cost and performance. Leads to performance guarantees.
- **Preliminary Design**:
- **Detailed Design and certification**
- **Launch**: (if at least 100 orders)
- **Cash Flow**: $ billion
- **Year**
  - 1.5
  - 4
  - -300 m
  - 9
  - 15
  - 400 aircraft
  - 80 b sales
  - -12 b
Breguet Range Formula

For a jet airplane:

\[
\frac{dW}{dt} = V \frac{dW}{dx} = -s_{fc} T = -s_{fc} \frac{W}{L/D}
\]

which subsequently leads to:

\[
dx = -\frac{V}{s_{fc} D} \frac{L}{W} dW
\]

Flying at a fixed (VL/D), the airplane range is expressed as:

\[
R = \frac{V}{s_{fc} D} \log \frac{W_1}{W_2}
\]

where

- \(s_{fc}\) is the engine specific fuel consumption
- \(W_1\) is the take-off weight
- \(W_2\) is the landing weight

The Breguet equation clearly exposes the multidisciplinary nature of the design problem.

- A lightweight structure is needed to minimize \(W_1\)
- The specific fuel consumption is mainly the province of the engine manufacturers, and in fact, the largest advances during the last 30–years have been in engine efficiency
- The aerodynamic designer should try to maximize VL/D
Aerodynamic Design to Maximize VL/D
- the cruising speed should be increased until the onset of drag rise due to the formation of shock waves.
- Shock Wave
- the best cruising speed is the transonic regime

Limitation due to Buffet
- With increasing shock strength, the pressure jump separates the flow
- This leads to buffet
- This sets the airplane performance limit

Typical Pattern of Transonic Flow over an Airfoil
- Sonic Line
- Shock Wave
- Boundary Layer
Effect of Drag Rise

- Drag Rise occurs at around Mach=0.85
- B747 flies at the transonic regime at M=0.85 with L/D=17
- Concorde flies supersonic at M=2 with L/D=7
Attained L/D for Airplanes

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-3</td>
<td>13</td>
</tr>
<tr>
<td>B717</td>
<td>14</td>
</tr>
<tr>
<td>B707</td>
<td>18.6</td>
</tr>
<tr>
<td>B747-400</td>
<td>19.4</td>
</tr>
<tr>
<td>B777</td>
<td>19.7</td>
</tr>
<tr>
<td>B787</td>
<td>20.8</td>
</tr>
<tr>
<td>A380</td>
<td>19.9</td>
</tr>
<tr>
<td>Global Flyer</td>
<td>37</td>
</tr>
<tr>
<td>Best Sailplanes</td>
<td>60</td>
</tr>
<tr>
<td>Concorde</td>
<td>7.5 (Mach 2)</td>
</tr>
<tr>
<td>SR-71</td>
<td>6 (Mach 3)</td>
</tr>
</tbody>
</table>

2D Laminar Airfoil: 500
Global Hawk

General characteristics

- Crew: 0
- Length: 44 ft 5 in (13.54 m)
- Wingspan: 116 ft 2 in (35.41 m)
- Height: 15 ft 2 in (4.62 m)
- Empty weight: 8,490 lb (3,851 kg)
- Gross weight: 22,900 lb (10,387 kg)
- Powerplant: 1 × Allison Rolls-Royce AE3007H turbofan engine, 7,050 lbf (31.4 kN) thrust

Performance

- Cruise speed: 404 mph (351 kn; 650 km/h)
- Endurance: 36 hours
- Service ceiling: 65,000 ft (19,812 m)

Global Flyer

General characteristics

- Crew: 1
- Length: 44 ft 1 in (13.44 m)
- Wingspan: 114 ft 0 in (34.75 m)
- Height: 13 ft 3 in (4.05 m)
- Empty weight: 3700 lb (1678 kg)
- Fuel weight: 18100 lb
- Gross weight: 22100 lb (10024 kg)
- Powerplant: 1 Williams FJ44-2 turbofan, 2300 lbf (11.01 kN)

Performance

- Maximum speed: 196 mph (315 km/h)
- Range: 19,000 miles (35,188 km)
- Service ceiling: 51,000 ft (15,444 m)
- Maximum glide ratio: 37
Control Theory
Approach to Design

A wing is a device to control the flow. Apply the theory of
control of partial differential equations (J.L. Lions) in
conjunction with CFD.

References:
• Pironneau (1964) Optimum shape design for subsonic potential flow
• Jameson (1988) Optimum shape design for transonic and supersonic flow
  modeled by the transonic potential flow equation and the Euler equations
Application: Low Sweep Wing Redesign using RK-SGS Scheme

Mesh size=256x64x48, Design Steps=15, Design variables=127x33=4191 surface mesh points
<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1912</td>
<td>Bernstein polynomials</td>
</tr>
<tr>
<td>1946</td>
<td>Schoenberg coins the name “spline”</td>
</tr>
<tr>
<td>1959</td>
<td>de Casteljau algorithm</td>
</tr>
<tr>
<td>1966–1972</td>
<td>Bézier curves and surfaces</td>
</tr>
<tr>
<td>1971, 1972</td>
<td>Cox-de Boor recursion</td>
</tr>
<tr>
<td>1972</td>
<td>B-splines</td>
</tr>
<tr>
<td>1975</td>
<td>NURBS</td>
</tr>
<tr>
<td>1978</td>
<td>Catmull–Clark and Doo–Sabin subdivision surfaces</td>
</tr>
<tr>
<td>1980</td>
<td>Oslo knot insertion algorithm</td>
</tr>
<tr>
<td>1987</td>
<td>Loop subdivision</td>
</tr>
<tr>
<td>1987, 1989</td>
<td>Polar forms, blossoms</td>
</tr>
<tr>
<td>1996–present</td>
<td>Triangular and tetrahedral B-splines</td>
</tr>
<tr>
<td>2003</td>
<td>T-splines</td>
</tr>
</tbody>
</table>
The Basics of Computer Aided Design

2D CAD Representation and Mesh

3D CAD Representation and Mesh
CAD Application in Aircraft Design and Manufacturing

3D Fly-Thru

Full-Motion Human Modeling

Digital Pre-Assembly of a Boeing Airplane
• The Role of Onboard Computing
Accident Happens…Bad Luck

- A chain of unfortunate events can occur
  - Classic case, Cali, Colombia, Dec 20, 1995
  - A result of pilot error and bad luck
  - But could potentially be avoided with a fly-by-wire system in its final attempt to recover from crash

Accident Happens…Pilots

- There are more than 300,000 airline pilots in the world
- Some incompetent from the start
  - Most recent incident, Buffalo, NY, Feb 12, 2009
  - Pilot overpowered automatic stick pusher
  - The airplane stalled as a result and 49 killed
  - Could potentially be avoided if automatic protection was not overridden

The Need for Fly-by-Wire

- Plenty of once-excellent pilots grow unsafe with time
  - A320 ‘aerial baptism’, Mulhouse, France, Jun 26, 1988
- Personalities and national cultures can matter as much as experience in flight
- Employment seniority can outweigh performance
**Fly-by-Wire System**

**Fly-by-wire control systems**
- replaces manual control of the aircraft with an electronic interface
- movements of flight controls are converted to electronic signals transmitted by wires
- flight control computers determine how to move the actuators at each control surface to provide the expected response
- using electrical control circuits combined with computers, designers can save weight, improve reliability, and use the computers to mitigate the undesirable characteristics

**Mechanical and hydro-mechanical flight control systems**
- heavy and require careful routing of flight control cables through the aircraft using systems of pulleys, cranks, tension cables and hydraulic pipes
- redundant backup to deal with failures, which again increases weight.
- have limited ability to compensate for changing aerodynamic conditions which can lead to dangerous characteristics such as stall, spinning and pilot-induced oscillations
Example of A320 Flight Envelope Protection System:
Load Limit Protection
- prevent the pilot from overstressing the airplane
- never exceeding 2.5 G load limit

Stall Protection
- Three level of low-speed protection
  - Alpha Prot
    - at 10mph below min. speed
    - airplane automatic nose down to speed up
  - Alpha Floor
    - at even lower speed
    - automatically throttles to max. engine thrust
    - automatically retracts speed brakes
    - goes into emergence climb
  - Alpha Max
    - at slowest speed possible
    - full automatic intervention
    - balance the airplane at the edge of a stall

Fail Safe Technologies
- Damage Tolerance
- Automatic Control and Recovery of Airplane From Multiple Failures
- Made Possible by Advanced Electronics, Sensors and Software
- Example: Rockwell Collins Company
  - autonomously mitigate the effects of physical damage that could potentially occur in the air
  - surviving the effects of an adverse damage,
  - allowing the air vehicle to sustain flight and potentially continue its mission
  - instantaneous, autonomous assessment of damage incurred
  - followed by an immediate response that alters the flight control system to compensate for the effects of that damage

Successful flight demonstration of damage tolerant flight control and autonomous landing capabilities on an unmanned subscale F/A-18 on April 18, 2007 in Maryland.
Airborne Software

Software development for the Boeing 777

- 4 million lines of code, consisting of 2.5 million lines of newly developed software (6 times of previous Boeing airplane program) and commercial-off-the-shelf (COTS) software

Avionics control display application environment
(Source: DO-178B Software Considerations in Airborne Systems and Equipment Certification)
Unmanned Flight

Unmanned Aerial Vehicles (UAVs)
- an aircraft that flies without a human crew on board the aircraft
- historically, UAVs were simple remotely piloted aircraft
- but autonomous control is increasingly being employed in UAVs.

- UAVs come in two varieties
  - controlled from a remote location
  - fly autonomously based on pre-programmed flight plans using more complex dynamic automation systems
• **The Role of** Ground Based Computing in Flight Operations
Heavy Air Traffic Today

There are around 7,000 aircraft in the air over the United States at any given time.

Air Traffic Control

Needs computers to ensure:

- Safety
- Efficiency
- Increased Capacity
Next Generation Air Transportation System

- satellite based navigation and surveillance
- equivalent visual operations
- air traffic management system
- digital data exchange
- prognostic safety system
- informed decisions using integrated weather
Traffic Management Throughout All Phases of Flight

SURFACE TRAFFIC MANAGEMENT
Automation optimizes taxi routing. Provides controllers and pilots all equipped aircraft and vehicle positions on airport. Real-time surface traffic picture visible to airline, controllers and equipped operators. Surface movement management linked to departure and arrival sequencing. ADS-B and ASDE-X contribute to this function. Taxi times reduced and safety enhanced.

CRUISE
RNAV, RNP and RVSM utilize reduced separation requirements increasing airspace capacity. Aircraft fly most optimal path using trajectory-based operations considering wind, destination, weather, and traffic. Re-routes determined with weather fused into decision-making tools are tailored to each aircraft. Data Communications reduce frequency congestion and error. ADS-B routes available for equipped aircraft.

SURFACE TRAFFIC MANAGEMENT
Runway exit point, assigned gate and taxi route sent by Data Communications to pilots prior to approach. Pilot and controller workload reduced and safety improved.

SINGLE AUTHORITATIVE SOURCE
Operators and traffic managers have immediate access to identical weather information through one data source.

DEPARTURE MANAGEMENT
RNAV and RNP precision allow multiple departure paths from each runway. Departure capacity increased.

ARRIVAL MANAGEMENT
Arrival sequence planned hundreds of miles in advance. RNAV and RNP allow multiple precision paths to runway. Equipped aircraft fly precise horizontal and vertical paths at reduced power from descent point to final approach in almost all types of weather. Time and fuel are saved. Noise, emissions and holding are reduced.

ENHANCED SURFACE TRAFFIC OPERATIONS
Pilots and controllers talk less by radio. Data Communications expedites clearances, reduce communication errors. Pilot and controller workloads reduced.

PHASES OF FLIGHT
Mid-Term 2018
The Role of Computing in Airline Management

Online Flight Search

- Hotel
- Bus
- Car
- Flight
- Excursion

- One Way
- Return

- Destination From:
  - Select City

- To:
  - Select City

- Departure Date:
  - 08/15/2008

- Time:
  - 07
  - 30
  - 03

- Adults:
  - 01

- Children:
  - 01

- Senior:
  - 01

- Additional Options:
  - Airline Preference:
    - Select

- Class:
  - Business

- No. of Stops:
  - Select

- Search

Online Flight Tracking

(AA) American Airlines 88

- Departure: Tue - Oct 09, 2007
- Status: En Route - On Time
- On-Time Rating: 2.7 of 5

[Map Image]
Yield Management System in Airline Industry

Airline Yield Management System

- In a situation where cost and capacity is fixed while demand is fluctuating, the systems aim at
  - High load factors, as well as
  - High average yield

Forecasting: Use computers to store ‘booking history’, analyze characteristic pattern and forecast seats sold on the date of the flight

Capacity Control: if the forecast shows excess demand, low fares class will be closed to make room for high fare seats, and vice-versa

Role of Computers: make storing enormous amount of data, and execution of complicated analysis algorithm possible
The Future

- Increasing penetration of autonomous unmanned air vehicles (UAVs).
- Drones for delivering and surveillance.
- Unmanned commercial transport vehicles.
- Morphing with smart materials and embedded computers.
- Fusion of computing and flight technologies to match the capabilities of birds.
- Space tourism.
- Interplanetary flight.