“From Physics to Daily Life” Colloquium

Computers and Aviation

Antony Jameson
(FRS, FRAeS, FREng, Foreign Associate of NAE, Fellow of AIAA)
Thomas V. Jones Professor of Engineering
Department of Aeronautics and Astronautics
Stanford University

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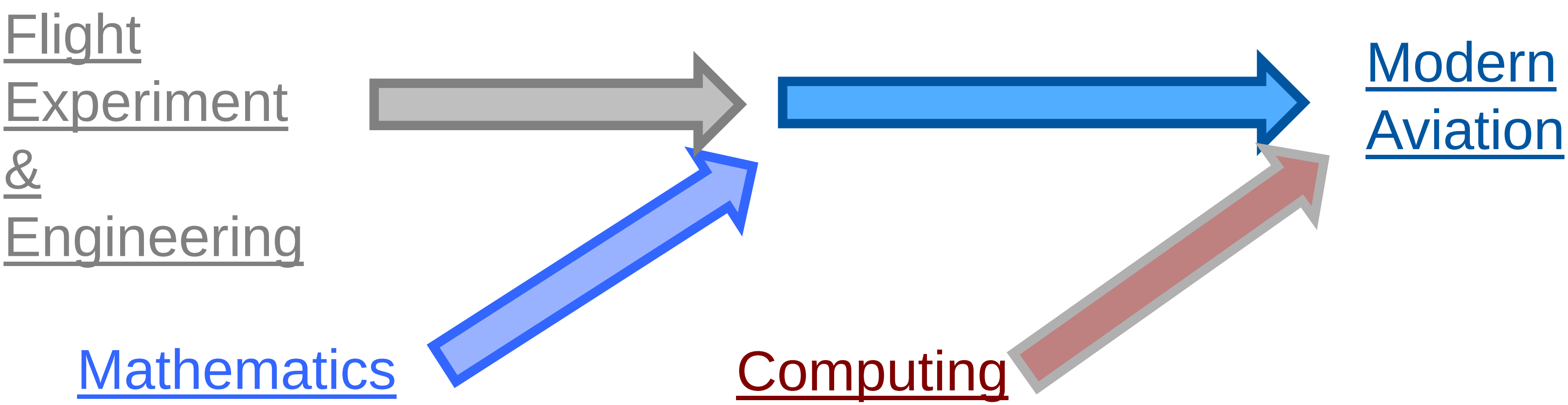
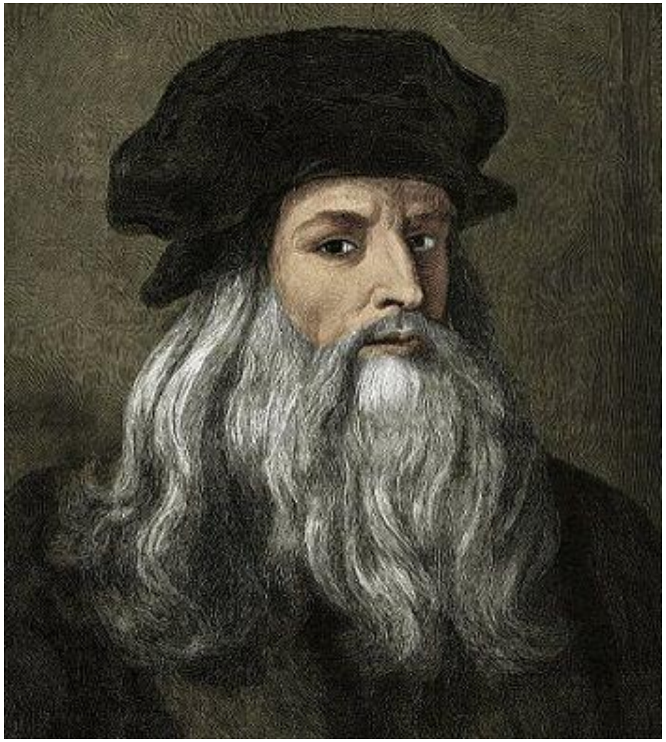
Objective

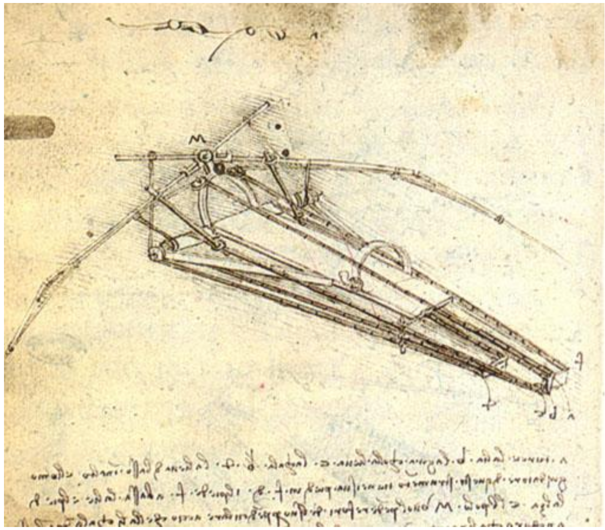
• To trace the parallel development of computing and flight over the last 300 years, culminating in a fusion of engineering, mathematics and computing in modern aviation.

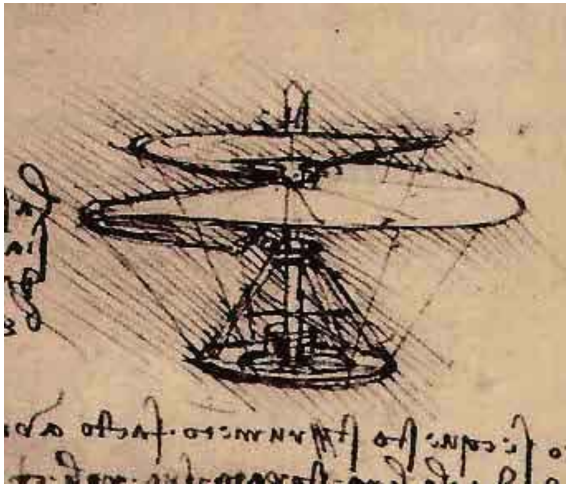
Fusion of Flight Experiments, Mathematics, and Computing:

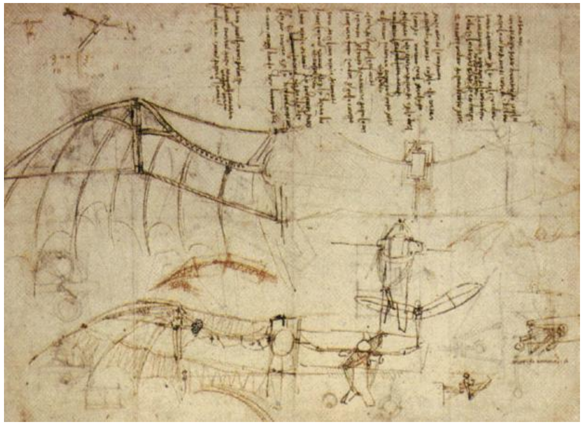


History of Aviation







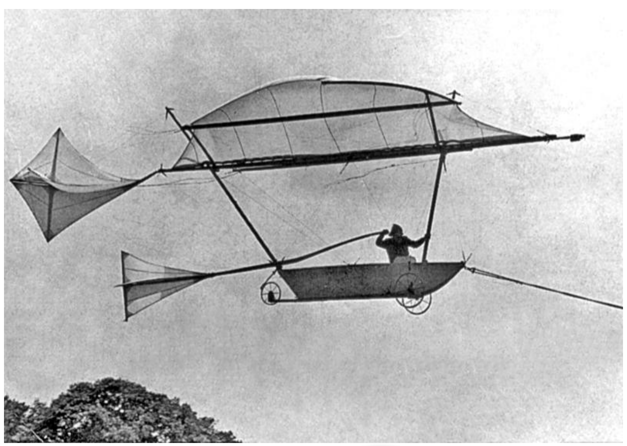


Leonardo da Vinci

- laid out various concepts of flying machines

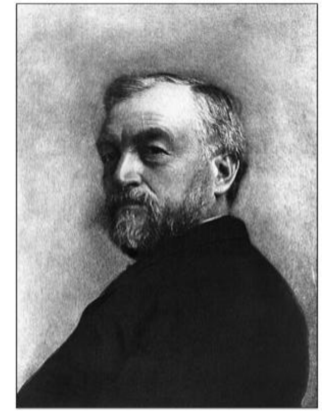
George Cayley (1799 – 1850's)

- identified the four aerodynamic forces
- set forth concept of the modern airplane
- built a successful human-carrying glider



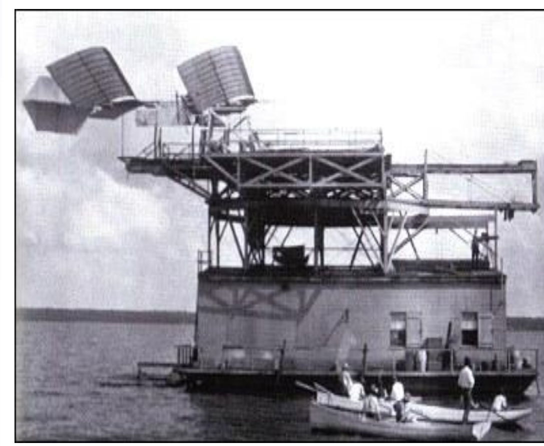
Otto Lilienthal

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

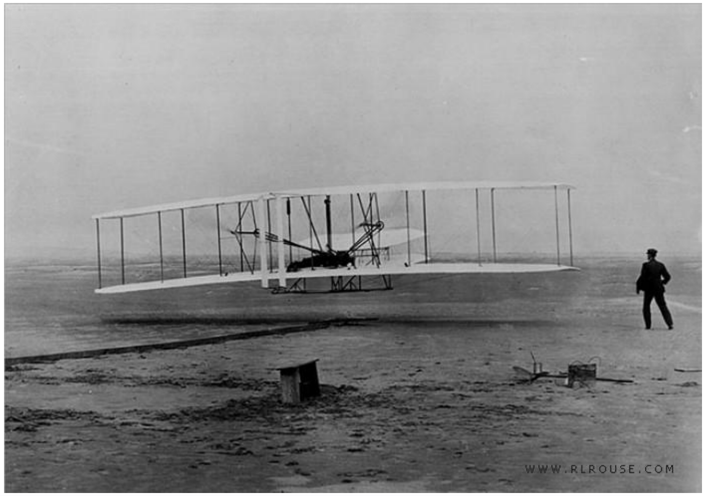


Samuel P. Langley (1896)

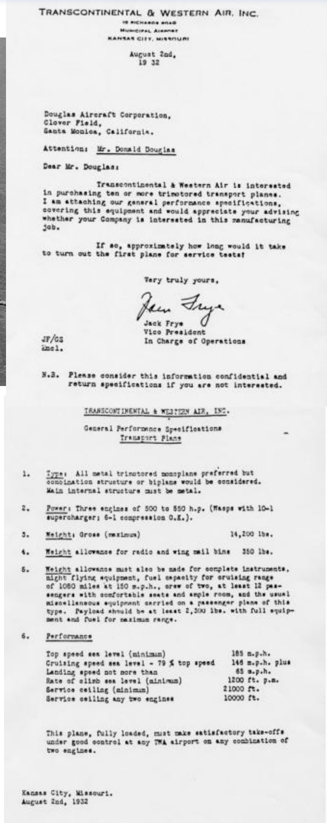
- built powered, heavier-than-air machine that had achieved sustained flight (no pilot)



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



TRANSCONTINENTAL & WESTERN AIR, INC.
KANSAS CITY, MISSOURI

August 2nd,
19 32

Douglas Aircraft Corporation,
Clover Field,
Santa Monica, California.

Attention: Mr. Donald Douglas

Dear Mr. Douglas:

Transcontinental & Western Air is interested in purchasing ten or more trimotored transport planes. I am attaching our general performance specifications, covering this equipment and would appreciate your advising whether your Company is interested in this manufacturing job.

If so, approximately how long would it take to turn out the first plane for service tests?

Very truly yours,

Jack Frye
Vice President
In Charge of Operations

JF/GS
Encl.

N.B. Please consider this information confidential and return specifications if you are not interested.

TRANSCONTINENTAL & WESTERN AIR, INC.

General Performance Specifications
Transport Plane

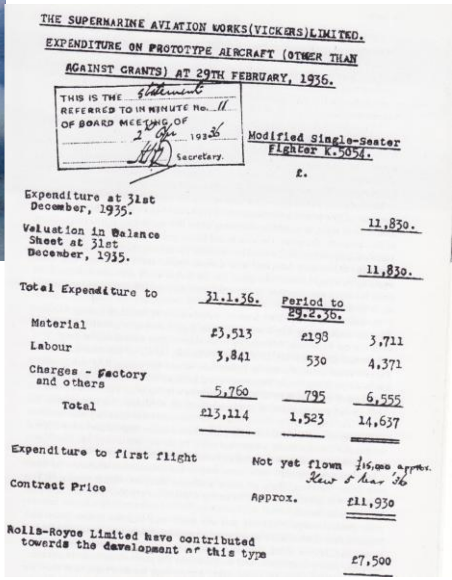
1. Type: All metal trimotored monoplane preferred but combination structure or biplane would be considered. Main internal structure must be metal.
2. Power: Three engines of 500 to 550 h.p. (Wasps with 10-1 supercharger; 6-1 compression O.K.).
3. Weight: Gross (maximum) 14,200 lbs.
4. Weight allowance for radio and wing mail bins 350 lbs.
5. Weight allowance must also be made for complete instruments, night flying equipment, fuel capacity for cruising range of 1080 miles at 150 m.p.h., crew of two, at least 12 passengers with comfortable seats and ample room, and the usual miscellaneous equipment carried on a passenger plane of this type. Payload should be at least 2,300 lbs. with full equipment and fuel for maximum range.
6. Performance

Top speed sea level (minimum)	185 m.p.h.
Cruising speed sea level - 79 % top speed	146 m.p.h. plus
Landing speed not more than	65 m.p.h.
Rate of climb sea level (minimum)	1200 ft. p.m.
Service ceiling (minimum)	21000 ft.
Service ceiling any two engines	10000 ft.

This plane, fully loaded, must make satisfactory take-offs under good control at any TWA airport on any combination of two engines.

Kansas City, Missouri.
August 2nd, 1932

Spitfire (1936)
- designed by R.J. Mitchell
Beverley Shenstone (Wing)



THE SUPERMARINE AVIATION WORKS(VICKERS)LIMITED.
EXPENDITURE ON PROTOTYPE AIRCRAFT (OTHER THAN AGAINST GRANTS) AT 29TH FEBRUARY, 1936.

THIS IS THE statement REFERRED TO IN MINUTE No. 11 OF BOARD MEETING OF 2nd Apr 1936
Secretary.

Modified Single-Seater Fighter K.5054.

			£.
Expenditure at 31st December, 1935.			11,830.
Valuation in Balance Sheet at 31st December, 1935.			11,830.
Total Expenditure to	31.1.36.	Period to 29.2.36.	
Material	£3,513	£198	3,711
Labour	3,841	530	4,371
Charges - Factory and others	5,760	795	6,555
Total	£13,114	1,523	14,637
Expenditure to first flight		Not yet flown	£15,000 approx.
Contract Price		Approx.	£11,930
Rolls-Royce Limited have contributed towards the development of this type			£7,500

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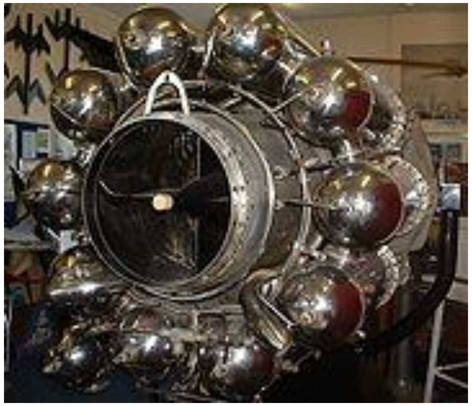
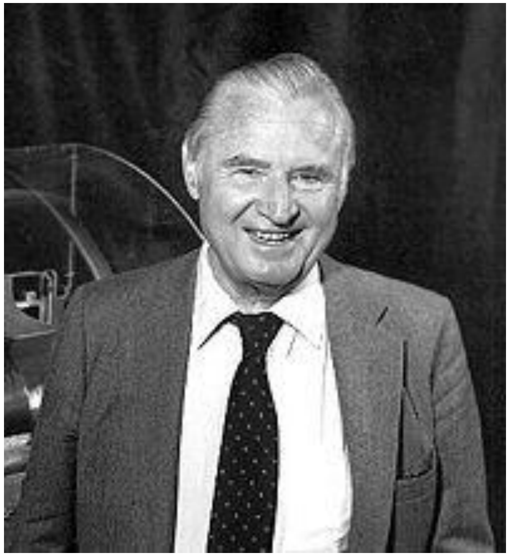
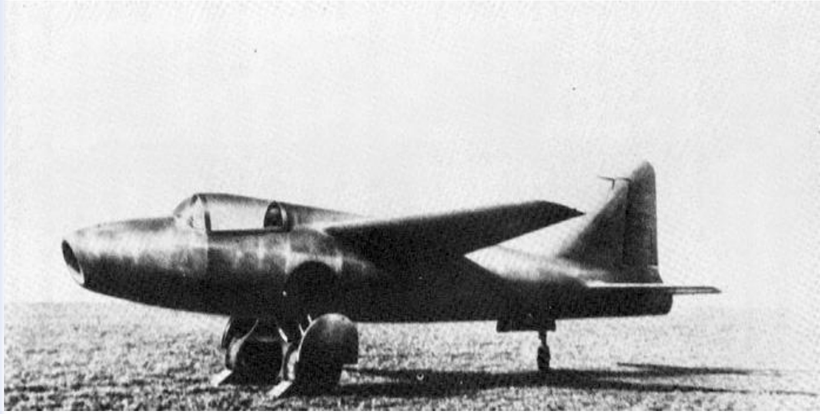
Frank Whittle
- patent (1930)
- built first engine (1937)



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



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



- Heinkel He 178

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ME 262 (1941)

SR 71 (1964)

• design led by Kelly Johnson and Ben Rich

Boeing 747 (1969)

• designed led by Joe Sutter

Airbus 380 (2005)

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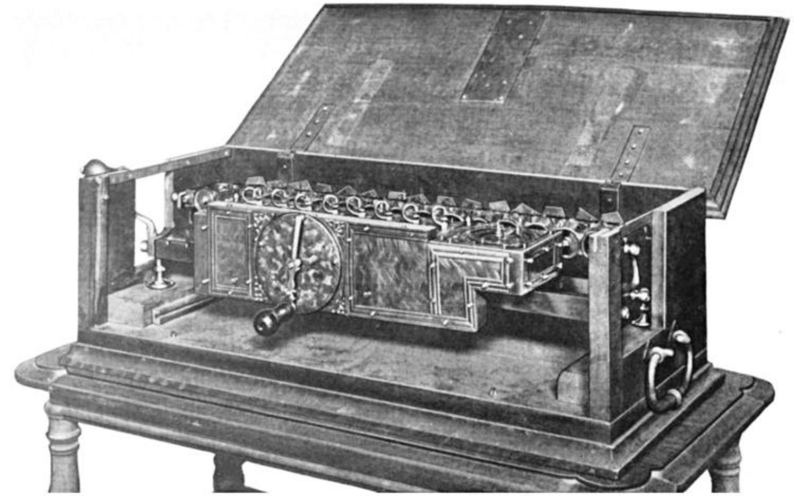
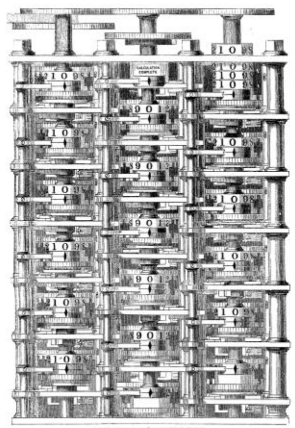
History of Computers

Pascal's Pascaline (1642)



Leibniz's Stepped Reckoner (1640's)



Babbage's Difference Engine and Analytic Engine (1822)

Jacquard's Loom (1801)

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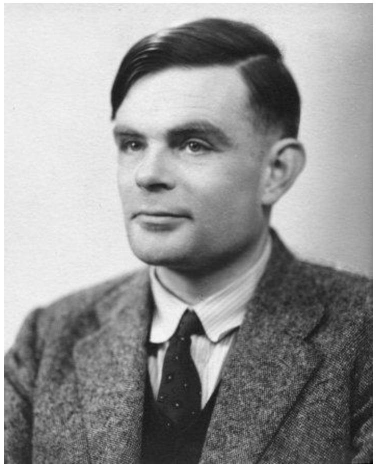
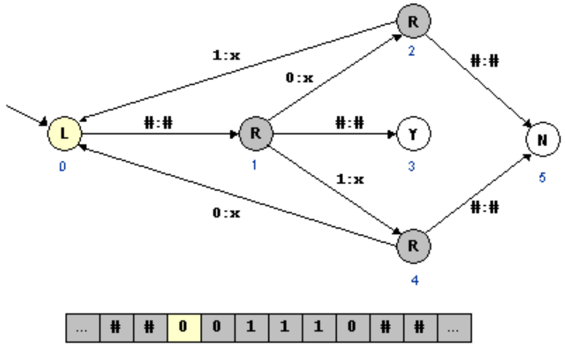
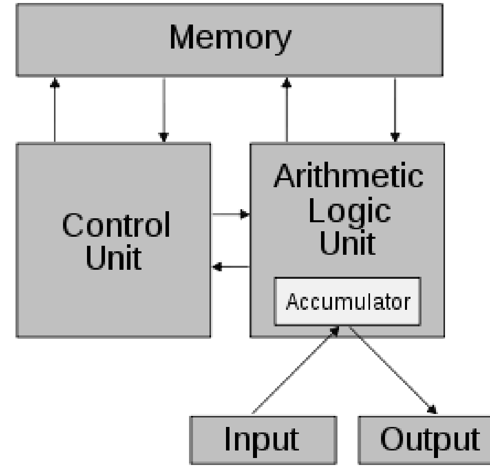
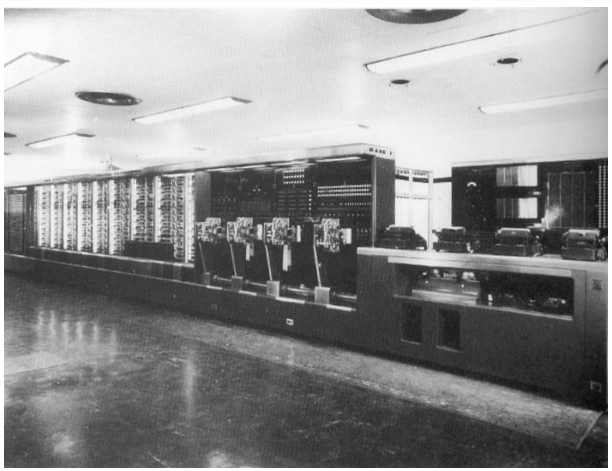




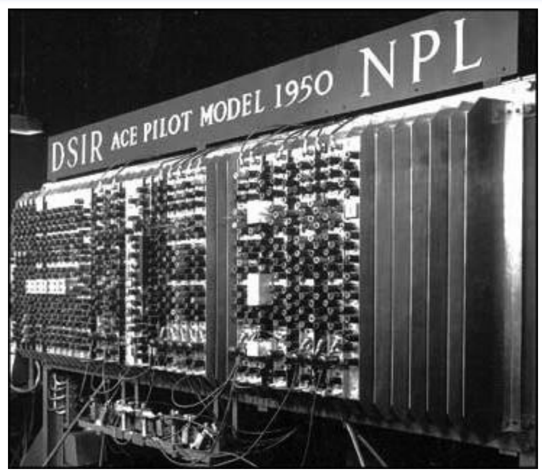
Alan Turing (1912-1954)
- Turing Machine



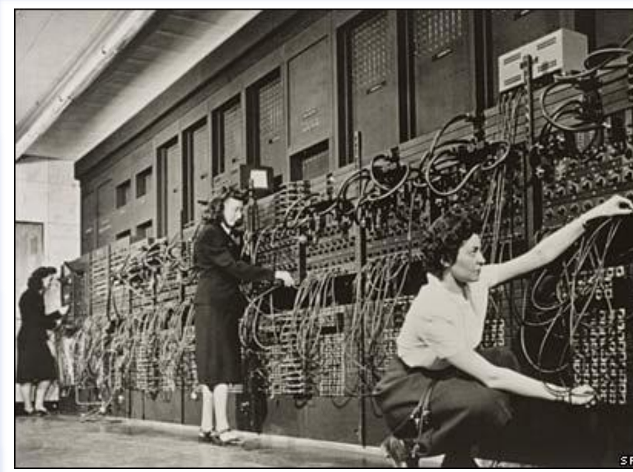
John von Neumann (1944)
von Neumann architecture



Mark I (1944)
- first programmable digital computer



ACE (1945)
- Automatic Computing Engine



ENIAC (1946)
- Electronic Numerical Integrator And Computer

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Supercomputers Timeline

Cray-1

Fujitsu Numerical Wind Tunnel

1964	CDC 6600	3 MFLOPS	
1969	CDC 7600	36 MFLOPS	AEC-Lawrence Livermore National Laboratory, California, USA
1974	CDC STAR-100	100 MFLOPS	
1975	Burroughs ILLIAC IV	150 MFLOPS	NASA Ames Research Center, California, USA
1976	Cray-1	250 MFLOPS	Energy Research and Development Administration (ERDA) Los Alamos National Laboratory, New Mexico, USA (80+ sold worldwide)
1981	CDC Cyber 205	400 MFLOPS	(~40 systems worldwide)
1983	Cray X-MP/4	941 MFLOPS	U.S. Department of Energy (DoE) Los Alamos National Laboratory; Lawrence Livermore National Laboratory; Battelle; Boeing
1984	M-13	2.4 GFLOPS	Scientific Research Institute of Computer Complexes, Moscow, USSR
1985	Cray-2/8	3.9 GFLOPS	DoE-Lawrence Livermore National Laboratory, California, USA
1989	ETA10-G/8	10.3 GFLOPS	Florida State University, Florida, USA
1990	NEC SX-3/44R	23.2 GFLOPS	NEC Fuchu Plant, Fuchū,_Tokyo, Japan
	Thinking Machines CM-5/1024	59.7 GFLOPS	DoE-Los Alamos National Laboratory; National Security Agency
1993	Fujitsu Numerical Wind Tunnel	124.50 GFLOPS	National Aerospace Laboratory, Tokyo, Japan
	Intel Paragon XP/S 140	143.40 GFLOPS	DoE-Sandia National Laboratories, New Mexico, USA
1994	Fujitsu Numerical Wind Tunnel	170.40 GFLOPS	National Aerospace Laboratory, Tokyo, Japan
	Hitachi SR2201/1024	220.4 GFLOPS	University of Tokyo, Japan
1996	Hitachi/Tsukuba CP-PACS/2048	368.2 GFLOPS	Center for Computational Physics, University of Tsukuba, Tsukuba, Japan
1997	Intel ASCI Red/9152	1.338 TFLOPS	DoE-Sandia National Laboratories, New Mexico, USA
1999	Intel ASCI Red/9632	2.3796 TFLOPS	

Supercomputers Timeline

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

2012 Sequoia 20 PFLOPS IBM

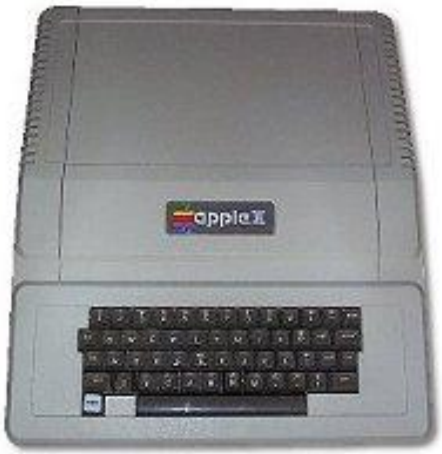

NEC Earth Simulator


IBM Blue Gene

Personal Computers

Xerox Alto 1973

Altair 1975



Apple II 1977

IBM PC 1981

PC Laptop and MacBook (2000's)

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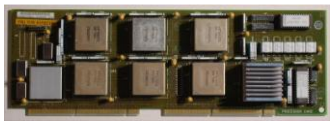
Microprocessor Timeline


8086


POWER CPU (IBM)

80386

Pentium

Core 2 Duo

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

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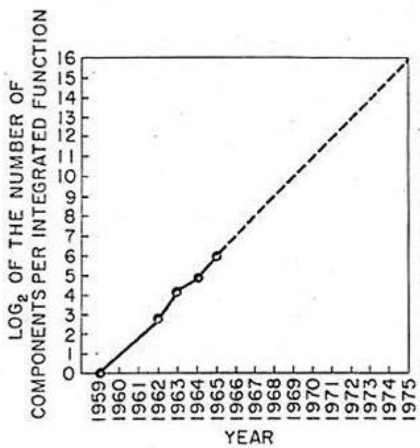
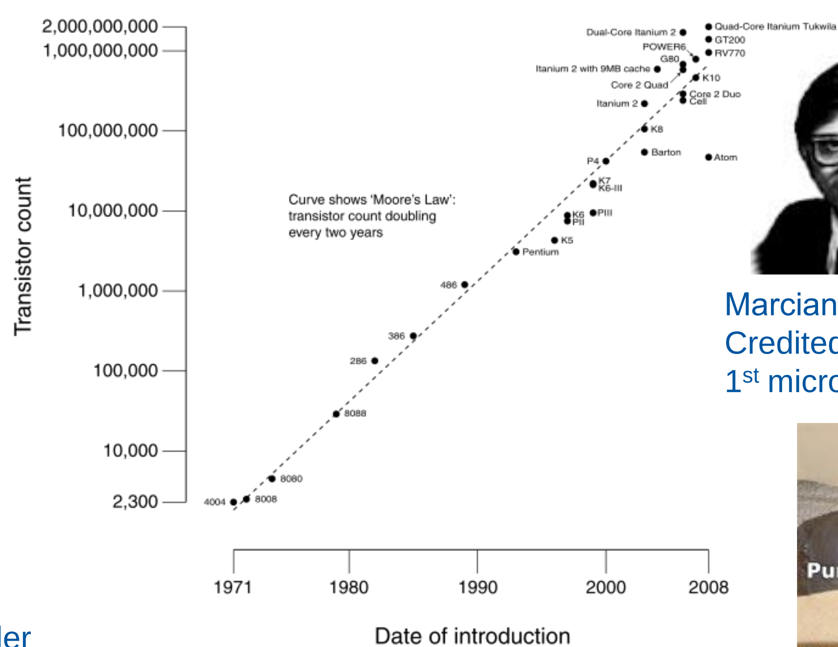
Microprocessor Progress – Intel

Moore's Law graph, 1965

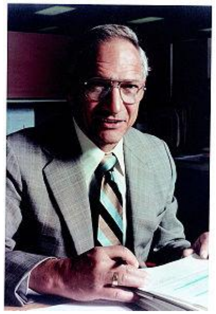


CPU Transistor Counts 1971-2008 & Moore's Law

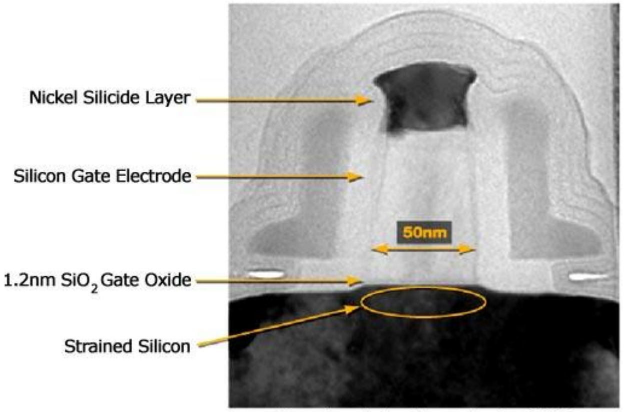


Gordon Moore
Intel Co-Founder

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



Robert Noyce
Intel Co-Founder



50nm transistor dimension is ~2000x smaller than diameter of human hair

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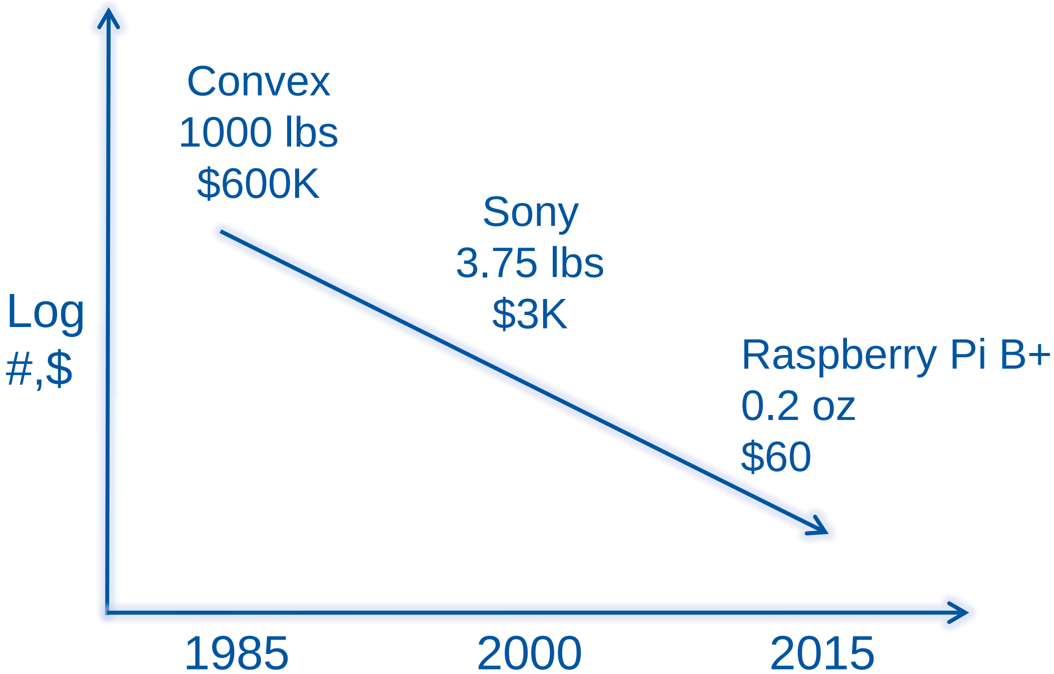
'Specific Computing Power' – Jameson and Vassberg (2001)

- 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

- **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

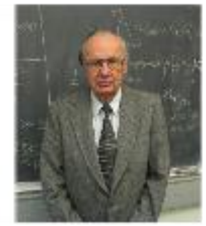
① First airplane with wing designed by CFD – Canadair Challenger (1977)
② First commercial aircraft with fly-by-wire – Airbus A320 (1982)
③ First commercial aircraft with digital design – Boeing B777 (1994)

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	$H(\mathrm{div})$, $H(\mathrm{curl})$, and $H(\mathrm{div}) \oplus H(\mathrm{curl})$ elements
1992–1996	Meshless methods


John Argyris


Ivo Babuška


Ted Belytschko


Franco Brezzi


Ray Clough


Richard Courant


J. Tinsley Oden


D. R. J. Owen


Pierre Arnaud Raviart


Leszek Demkowicz


Jim Douglas, Jr.


Richard Gallagher


Robert L. Taylor


Olgierd C. Zienkiewicz


Bruce Irons


Wing Kam Liu


Jean-Claude Nédélec

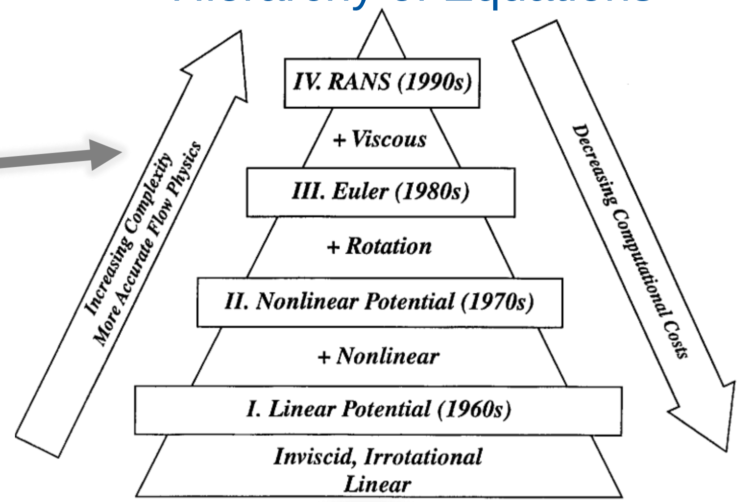
Emergence of CFD 1965–2005

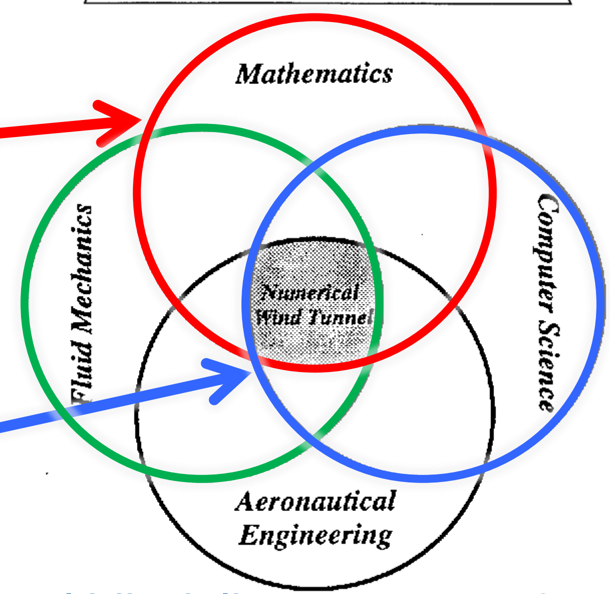
❖In 1960, the underlying principles of fluid dynamics and the formulation of the governing equations (potential flow, Euler, RANS) were well established.

❖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.

Hierarchy of Equations

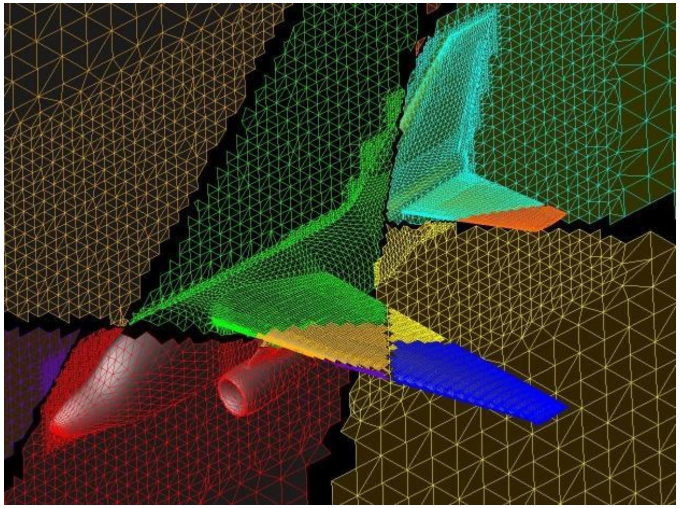




Multidisciplinary Nature of CFD

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

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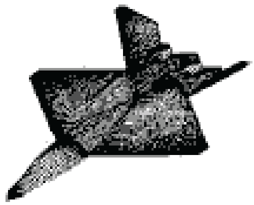
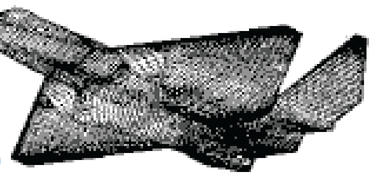
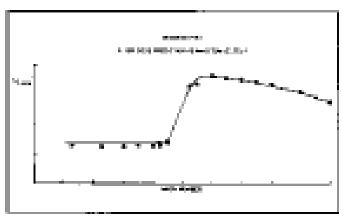
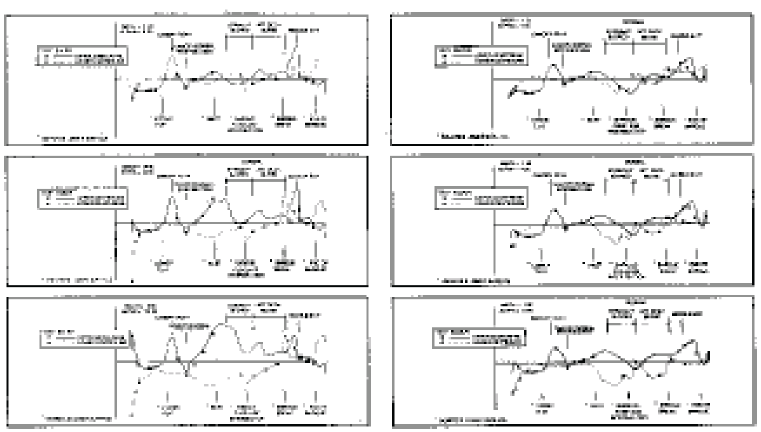
Examples: Northrop YF23, A320 and SST

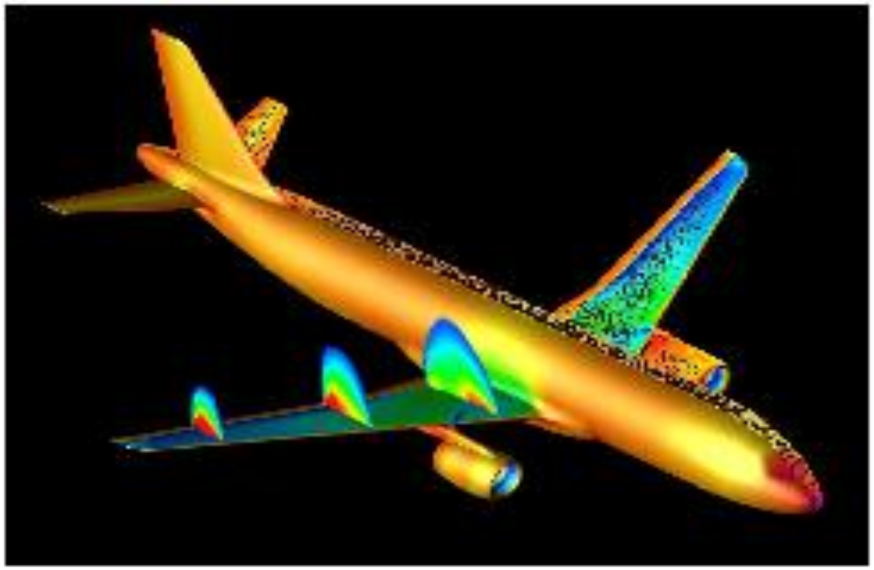


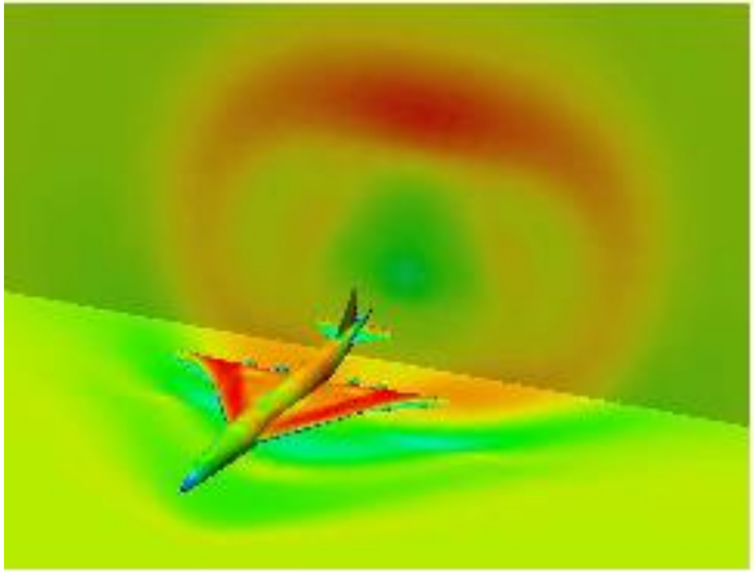


Euler Solutions
around 1985-1990





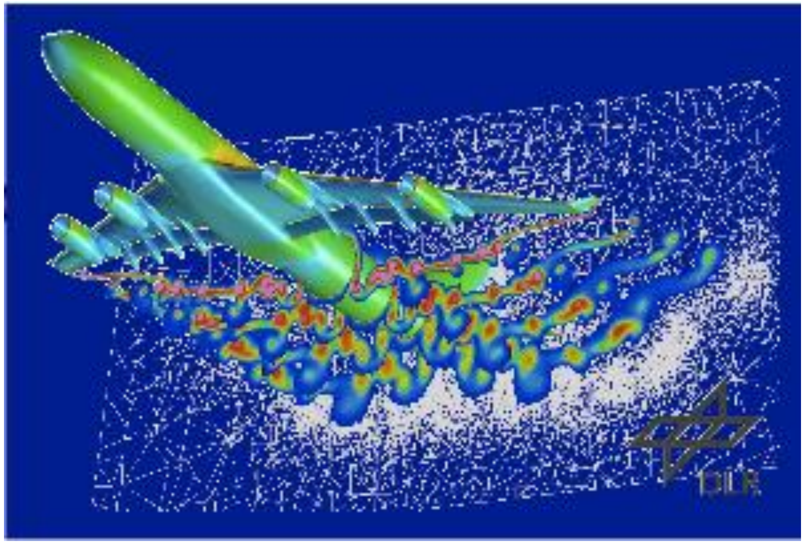


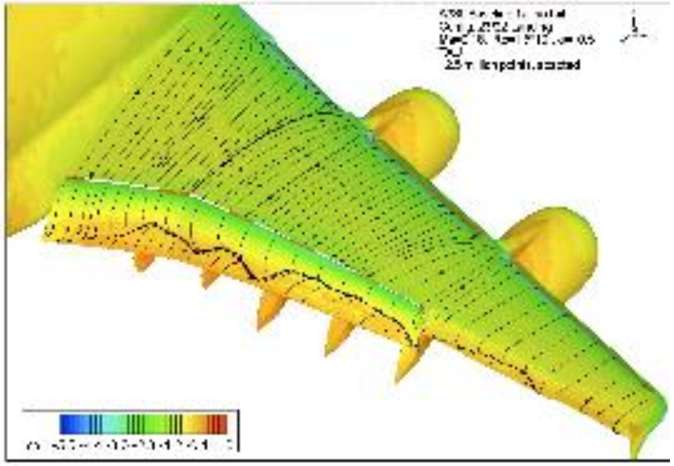


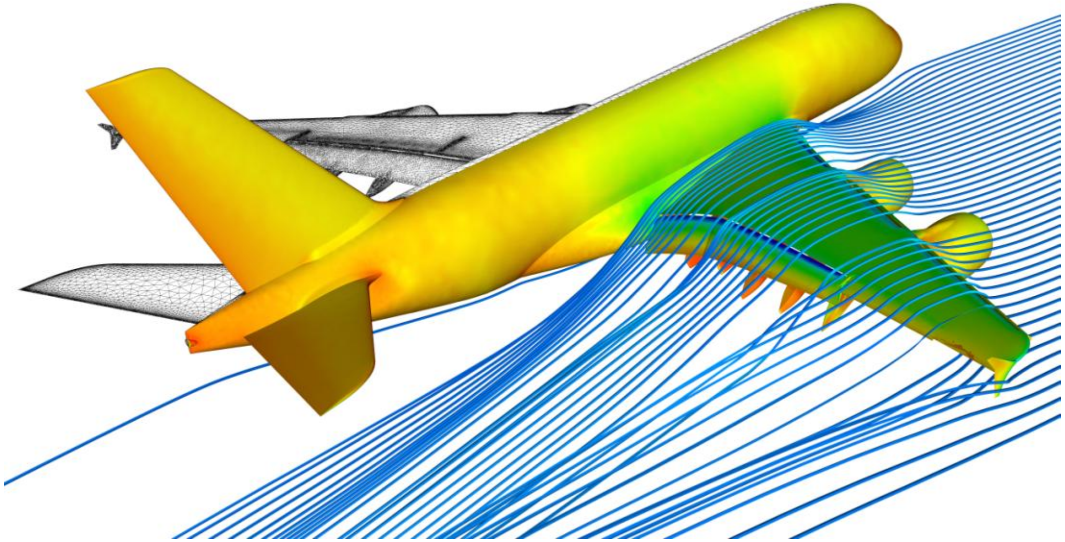
Examples: Unstructured TAU Code

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







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CFD Contributions to A380 & B787

Airbus A380

Boeing 787

History of Computer Aided Design (CAD)

Timeline: Milestones in CAD representations

1912	Bernstein polynomials
1946	Schoenberg coins the name "spline"
1959	de Casteljau algorithm
1966–1972	Bézier curves and surfaces
1971, 1972	Cox-de Boor recursion
1972	B-splines
1975	NURBS
1978	Catmull–Clark and Doo–Sabin subdivision surfaces
1980	Oslo knot insertion algorithm
1987	Loop subdivision
1987, 1989	Polar forms, blossoms
1996–present	Triangular and tetrahedral B-splines
2003	T-splines


Sergei Bernstein


Pierre Bézier


Ed Catmull


Jim Clark


Elaine Cohen


Carl de Boor


Rich Riesenfeld


Malcolm Sabin


Isaac Schoenberg


David Gu


Klaus Höllig


Charles Loop


Peter Schröder


Larry Schumaker

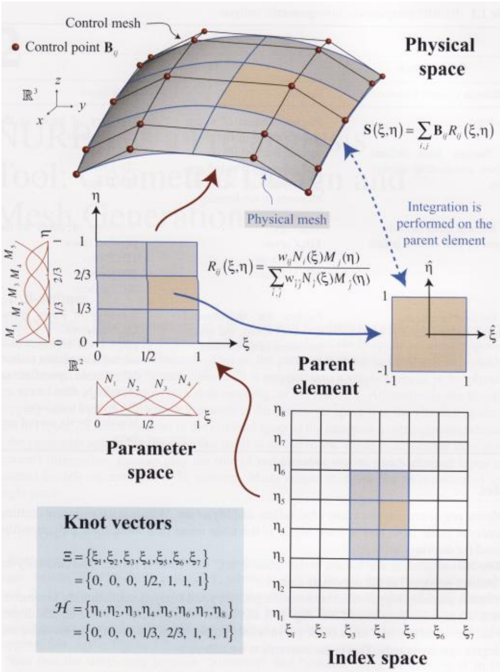

Tom Sederberg

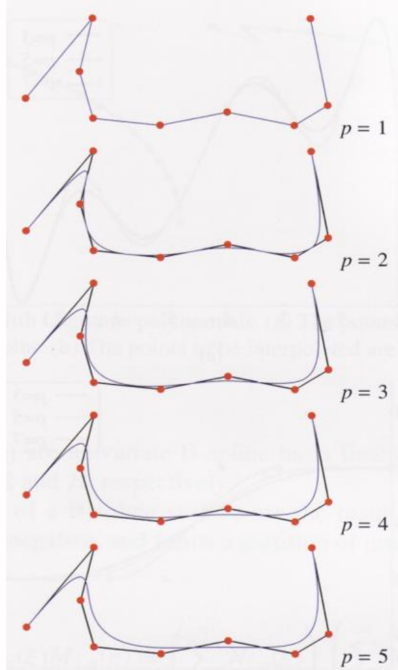

Tom Lyche


Jörg Peters


Ulrich Reif

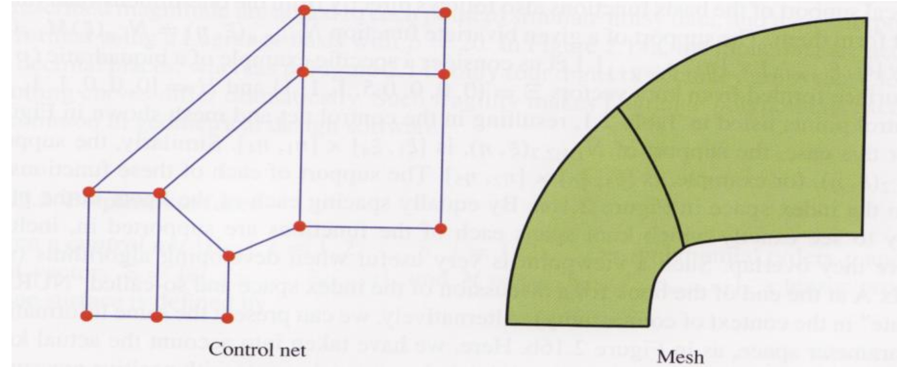
CAD using NURBS



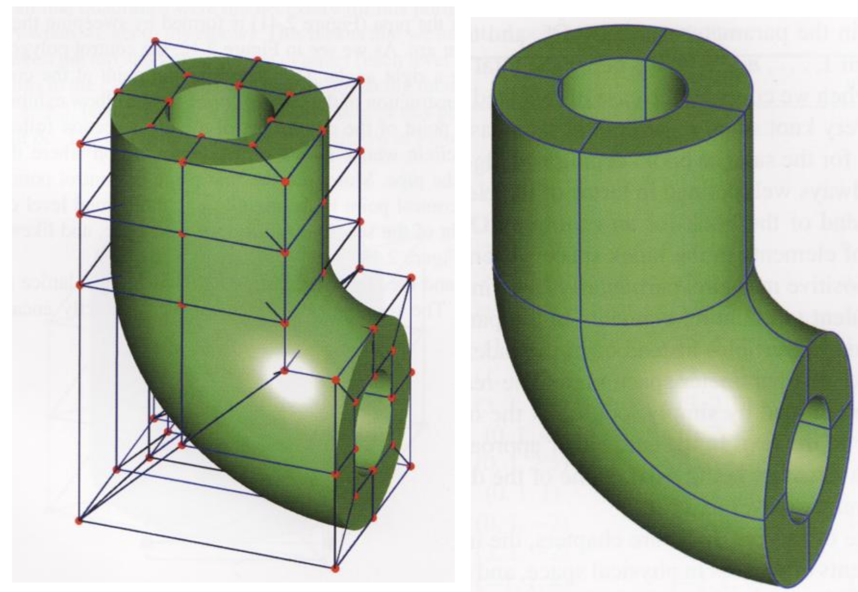


The Basics of Computer Aided Design

(a) Curve and control points (b) Curve and mesh denoted by knot locations



2D CAD Representation and Mesh



3D CAD Representation and Mesh

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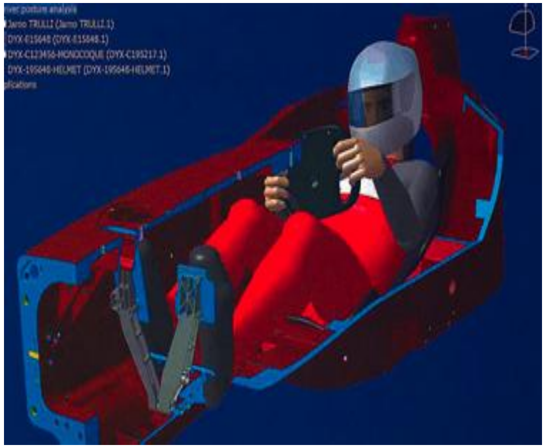
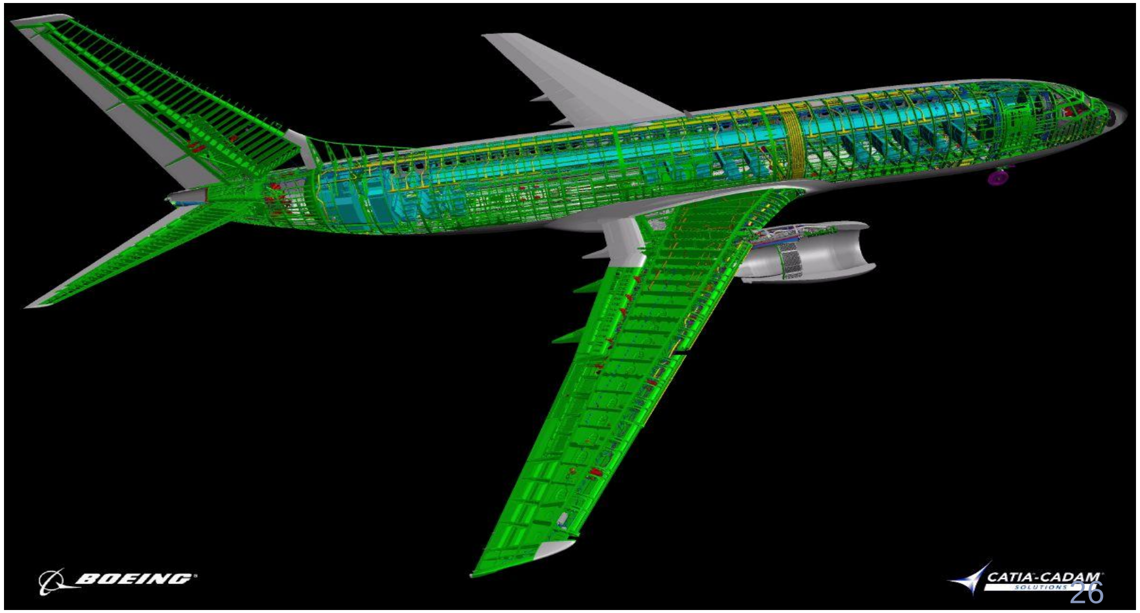
CAD Application in Aircraft Design and Manufacturing

3D Fly-Thru

Full-Motion Human Modeling



Digital Pre-Assembly of a Boeing Airplane



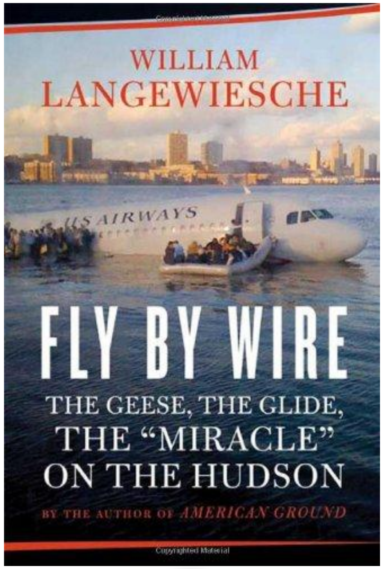
- The Role of Onboard Computing

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

The Need for Fly-by-Wire



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

❖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

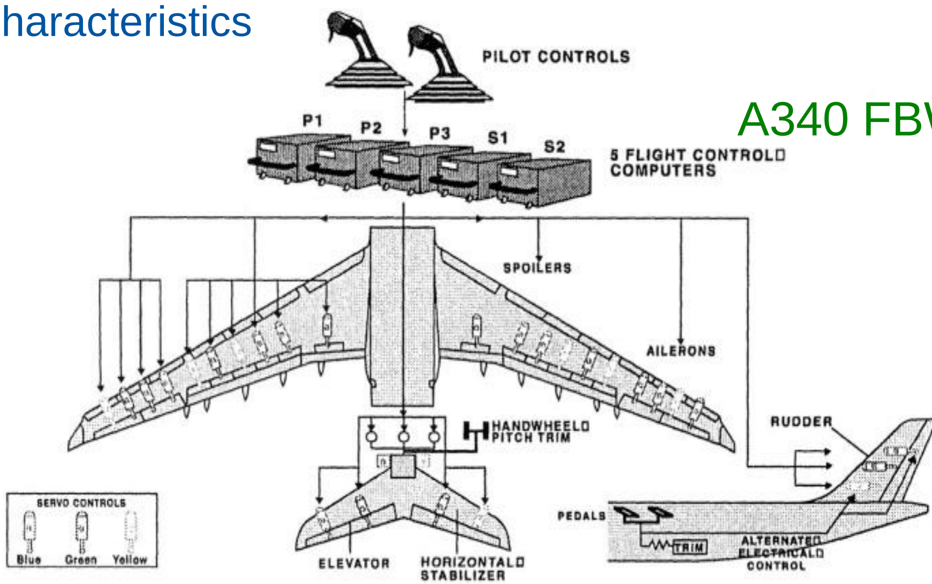
Fly-by-wire control systems

❖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

A340 FBW System



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

Damage Tolerance

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.

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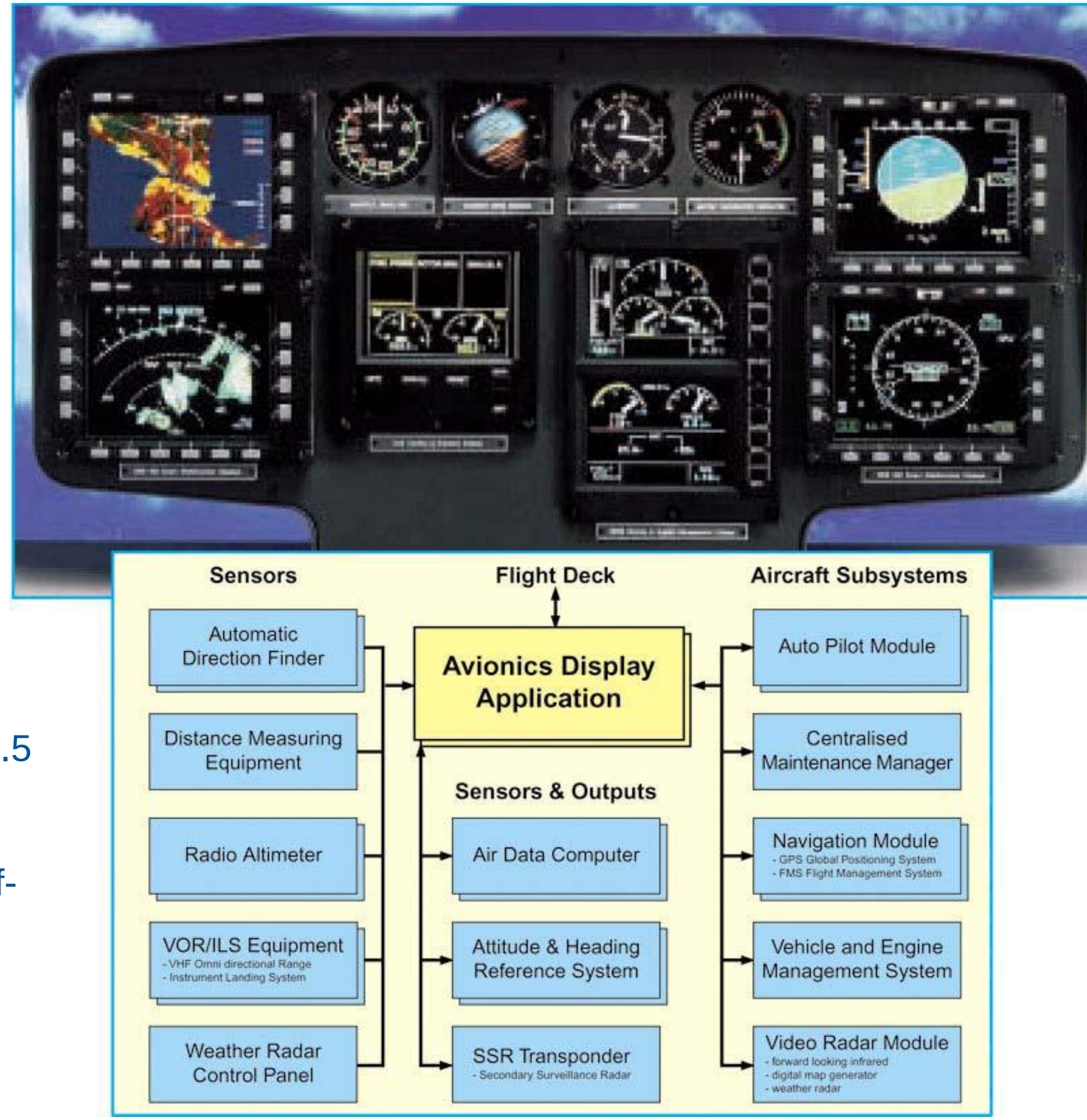
Airborne Software

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

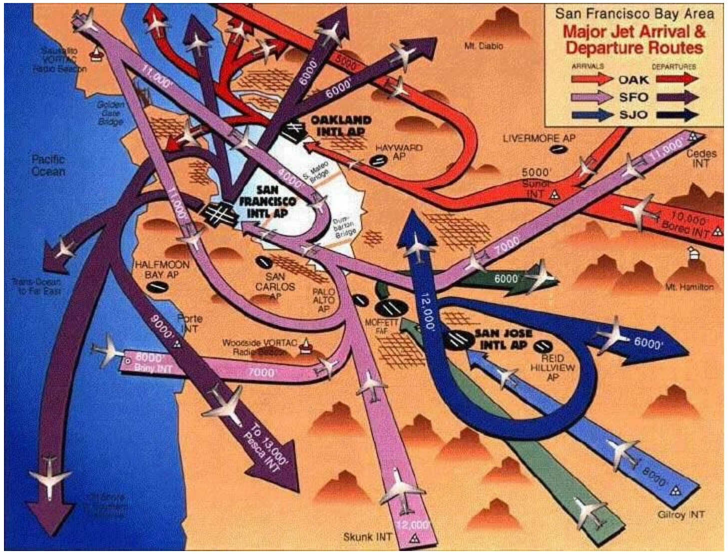
Unmanned Aerial Vehicles (UAVs)

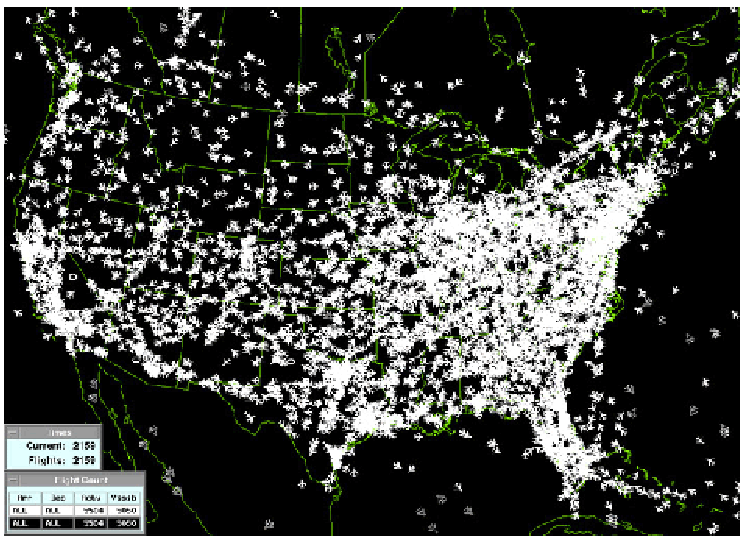
- an aircraft that flies without a human crew on board the aircraft
- historically, UAVs were simple remotely piloted aircraft
- but autonomous control is increasingly being employed in UAVs.

- 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

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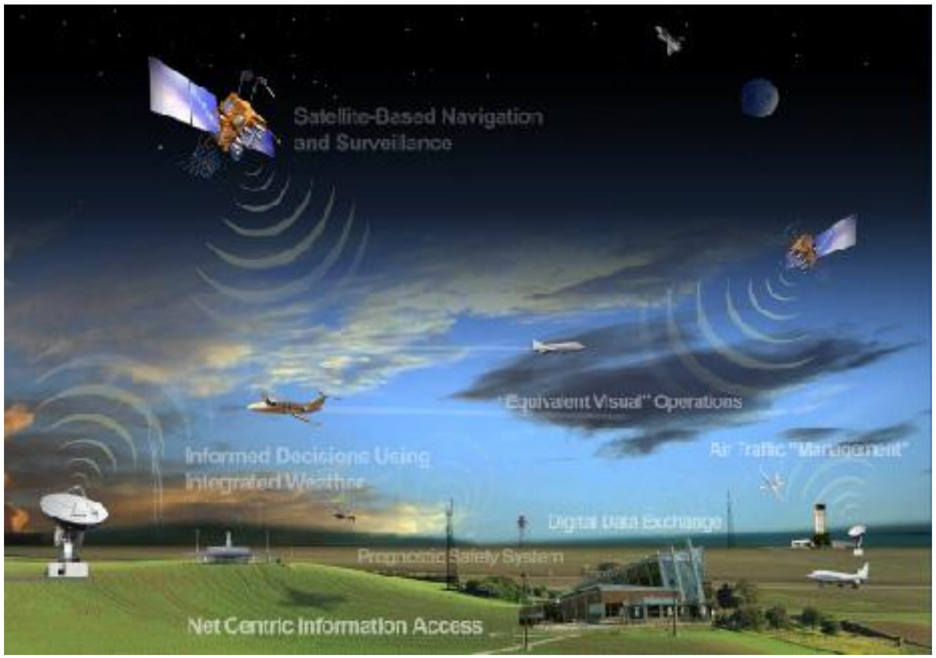
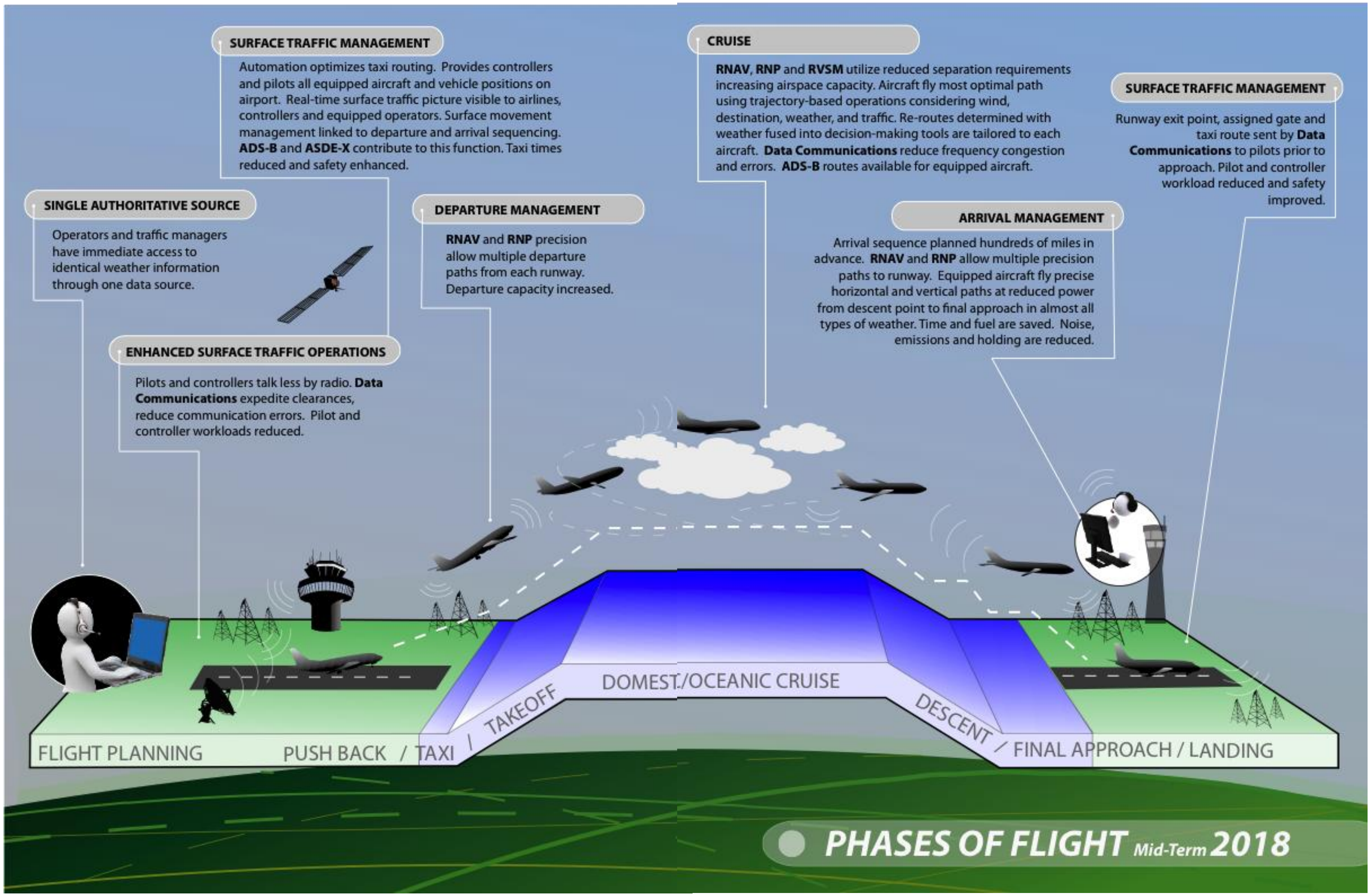
Next Generation Air Transportation System



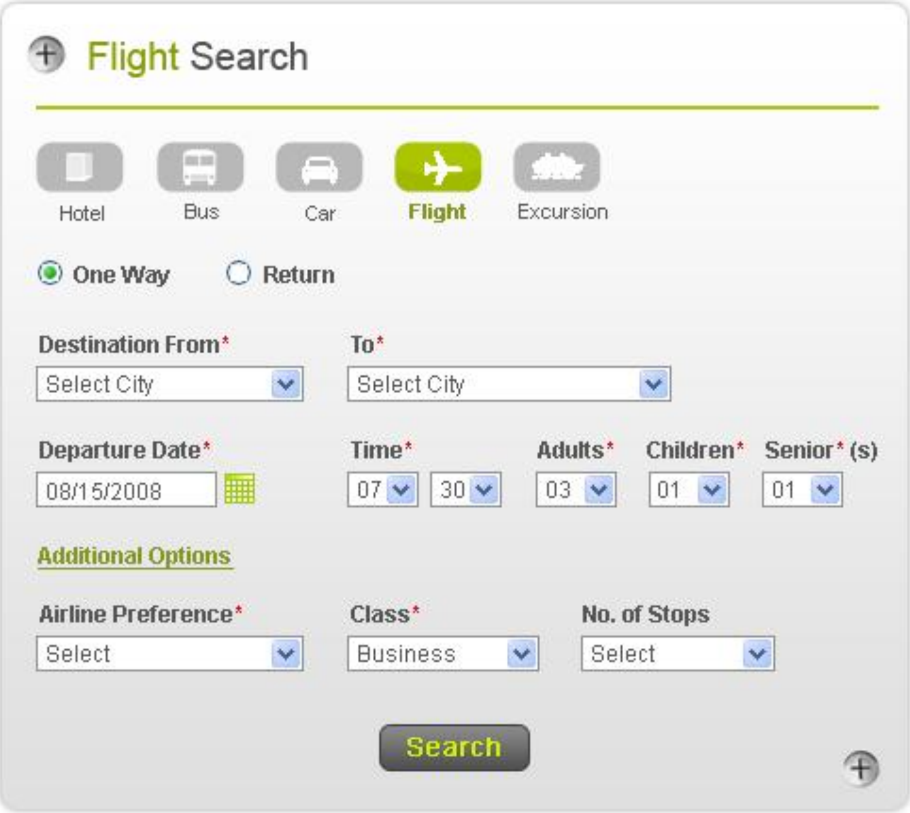
- satellite based navigation and surveillance
- equivalent visual operations
- air traffic management system
- digital data exchange
- prognostic safety system
- informed decisions using integrated weather

Traffic Management Throughout All Phases of Flight



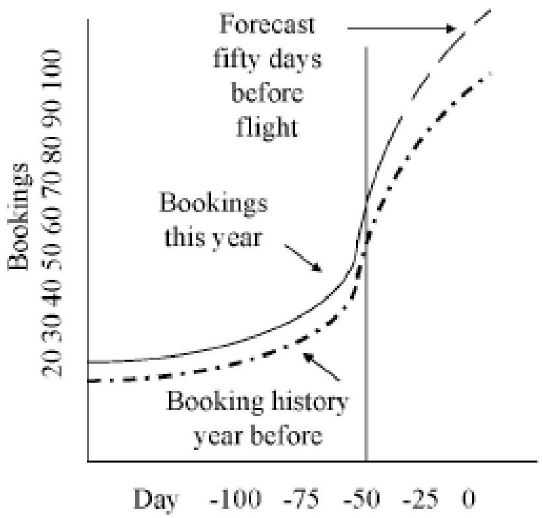
The Role of Computing in Airline Management

Online Flight Search

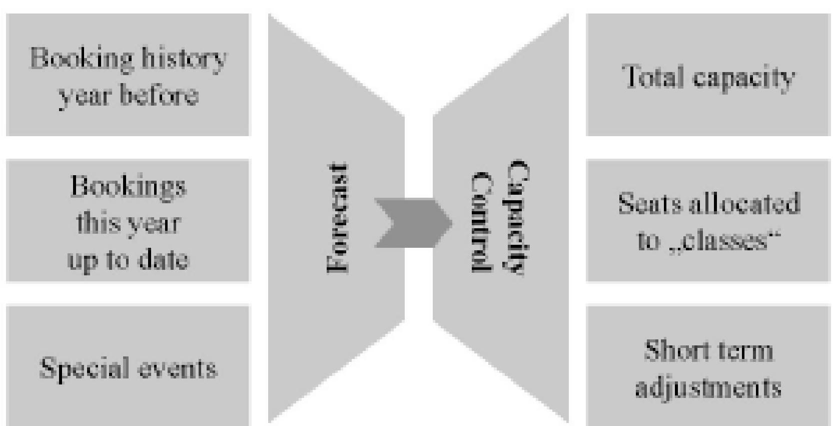


Online Flight Tracking

Yield Management System in Airline Industry



Booking history and forecast



Yield management architecture

- 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.

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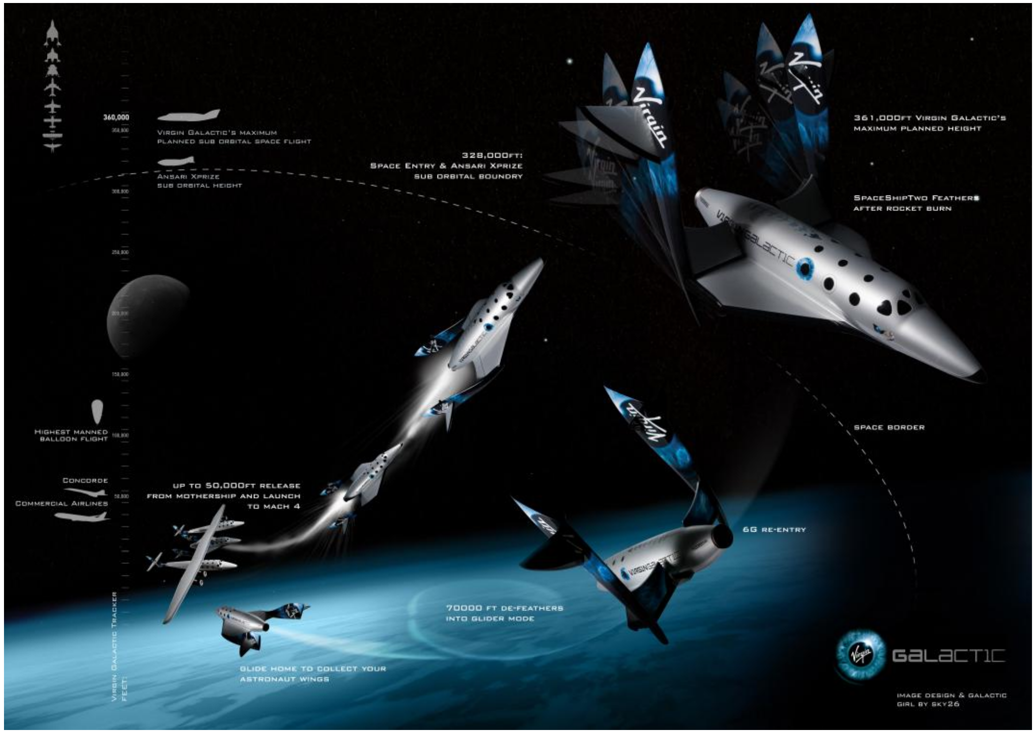

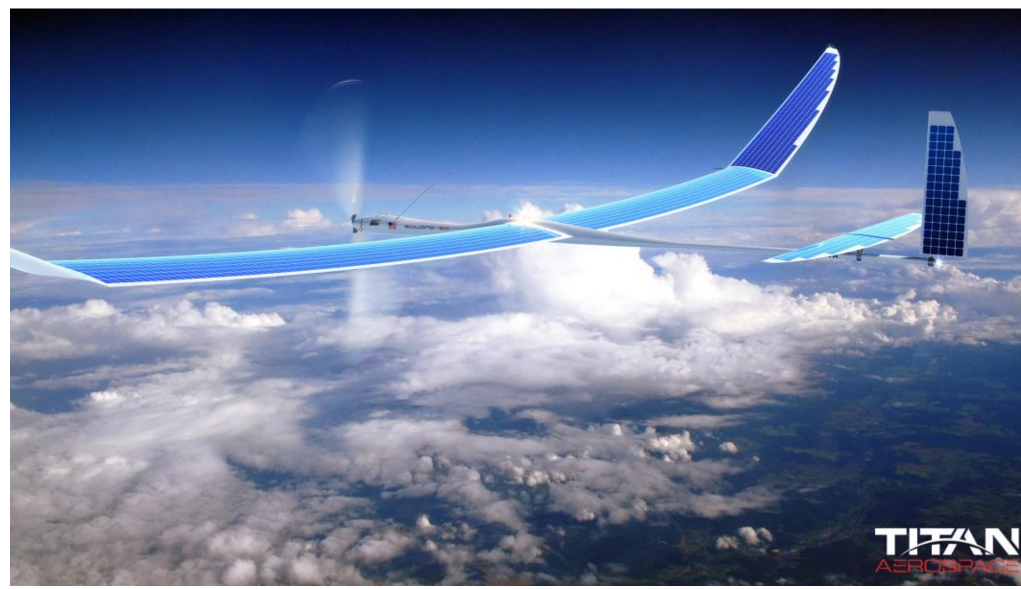

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