AE 651
Aerodynamics of Compressors and Turbines

A M Pradeep

ampradeep@aero.iitb.ac.in; Ph: 7125

Office: 208D; Office hours: 0900-1300 hrs. ; 1415-1730 hrs.

Course schedule: Tuesday: 1530-1655 hrs.

Friday: 1530-1655 hrs.

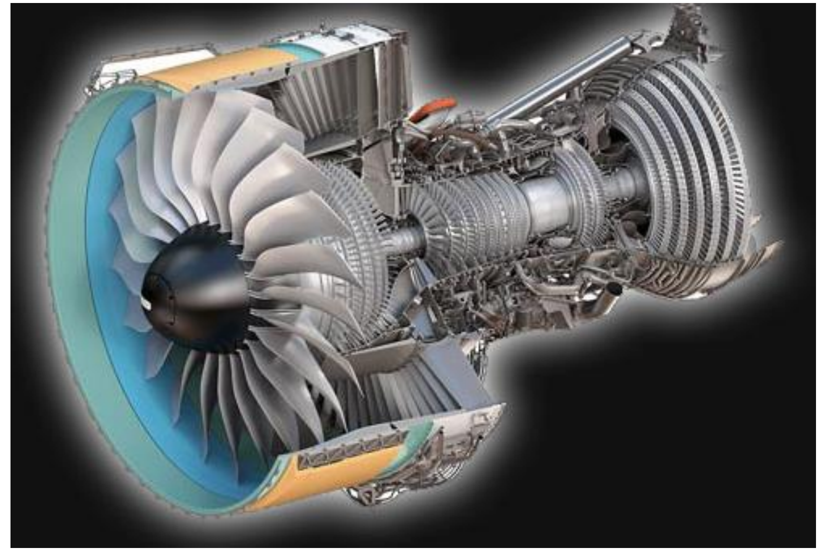
Venue: LT 302

Course web interface: moodle.iitb.ac.in

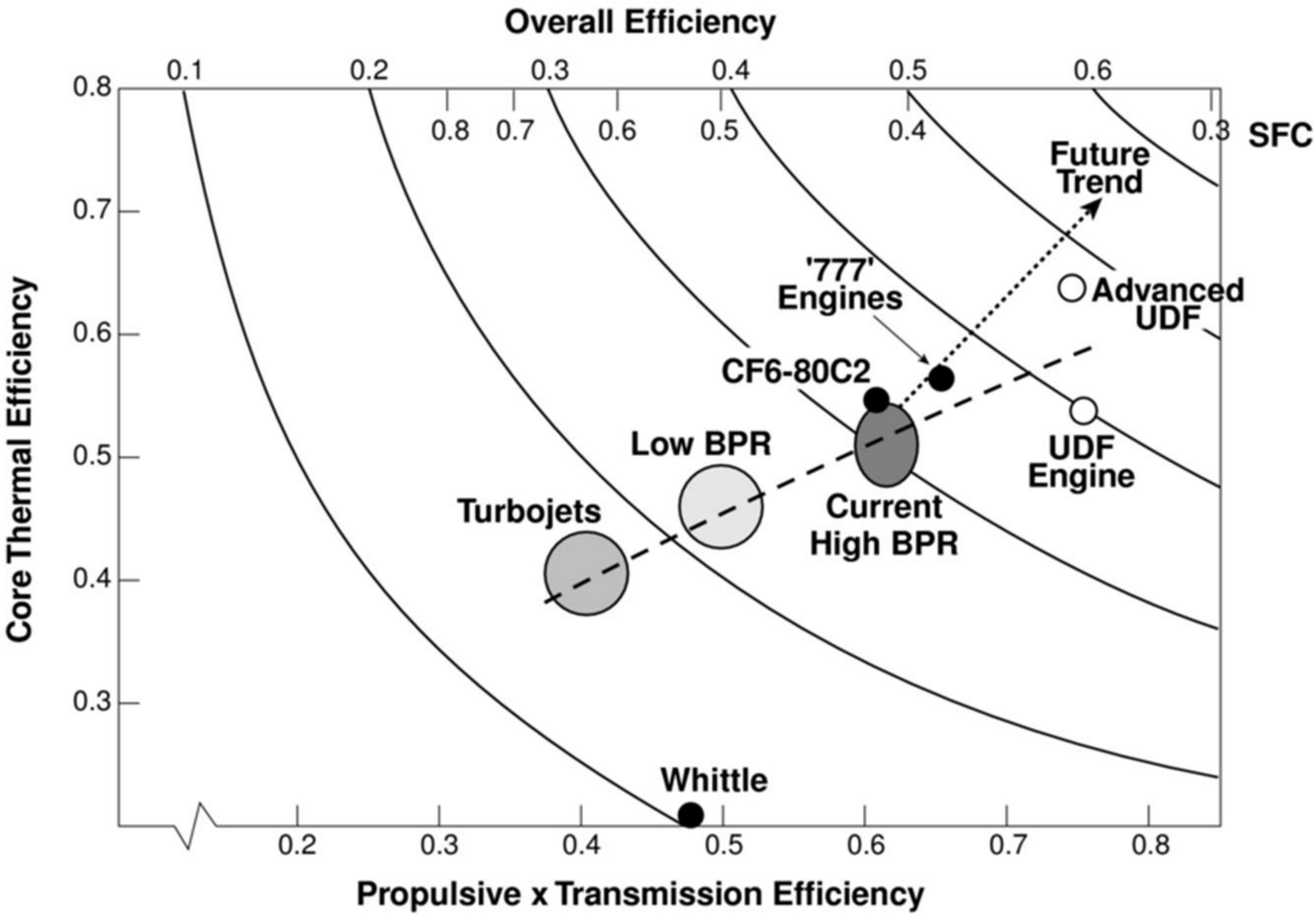
No future for aircraft gas turbine engines... !!!

National Academy of Sciences, Committee on Gas Turbines (June 1940):

"In its present state … the gas turbine engine could hardly be considered a feasible application to airplanes mainly because of the difficulty in complying with stringent weight requirements imposed by aeronautics."

Specs	Whittle Engine (1940)	Rolls Royce Trent 900 (2007)
Length/Dia	1.78 m/1.05 m	5.4 m/2.95 m
Dry Weight	431 kg	6246 kg
Max thrust	12.6 kN	370 kN
Overall pressure ratio	4:1	38:1
Turbine entry temp.	~ 1048 K	~ 1800 K
Thrust-weight ratio	2.6:1	6:1


Overall Efficiency
0.1
0.2
0.3
0.4
0.5
0.6
0.8
0.7
0.6
0.5
0.4
0.3
SFC
Future
Trend
'777'
Engines
Advanced
UDF
CF6-80C2
Low BPR
UDF
Engine
Turbojets
Current
High BPR
Whittle
Core Thermal Efficiency
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Propulsive x Transmission Efficiency

- Significant improvement in performance of engines since the 1940s.
- However, the core technologies remain nearly the same.
- Most engine OEMs have a set of standard “core” engines.
  - Other engines are developed around the core engine
- Engine technologies have a long development phase and will remain operational for decades
  - Eg: CFM-56 series, originally introduced in the 70s and continues to be operational although being phased out now.

- **Background**
  - Turbomachinery and internal aerodynamics requires cutting edge research
  - Several spin-off technology developments possible
  - “Self sufficiency” in rocket propulsion
  - Gas turbine propulsion ?
    - Dependence on the west → associated cost and limitations in technology transfer
  - Urgent need to initiate research activities in gas turbine technology
  - Bridge the gap in gas turbine research between India and the west.

- Applications for air, land and sea based power systems
  - Aero engines: civil, military
    - Turbojet, turbofan, turboprop and turboshaft
  - Marine propulsion: passenger, military and cargo
  - Land-based powerplants
  - Mobile powerpacks: civil and military
  - Mini/Micro gas turbines: portable powerpacks
  - Spacecraft auxiliary propulsion systems

Micro GT
~ mN

Mini GT
< 1N

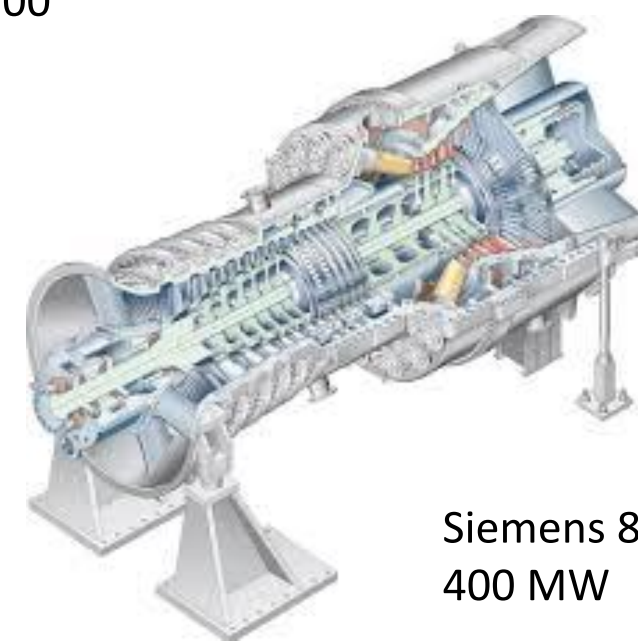
RC plane
30 N

GE-Snecma
90 kN

Rolls Royce Trent 900
370 kN

GE F414
98 kN

GE LM6000
50 MW



Siemens 8000H
400 MW

Some impressive numbers....

- An SGT5-8000H gas turbine has the same capacity as 1200 Porsche 911 Turbo cars.

- An SGT5-8000H gas turbine weighs as much as one fully fueled Airbus A380.

- An SGT5-8000H gas turbine produces sufficient energy to supply a city with approx. 2.2 million inhabitants.

- A single SGT5-8000H gas turbine blade produces as much power as 11 Porsche 911 Turbo cars.

- Centrifugal force acting on jet pilots 7 g
- Centrifugal force acting on 8000H turbine 10,000 g blade (that is equal to 10,000 times its dead weight)

- Aims of this course
  - Fundamental understanding of working of compressors and turbines
  - Aerothermodynamics of compressors and turbines
  - Preliminary design of axial compressors/turbines
  - Performance evaluation of turbomachinery
  - Loss identification and estimation
  - Primary focus: turbomachinery for aero engine application

Course outline

- **Introduction to Turbomachinery**
- **Axial flow compressors and Fans:** Introduction; Aero-Thermodynamics of flow thru' axial flow compressor stage; Losses in axial flow compressor stage; Losses and Blade performance estimation; Secondary flows (3-D); Tip leakage flow and scrubbing; 3-D flow analysis; Radial Equilibrium Equation; Axial compressor characteristics; Design of compressor blades-2-D blade designs; Airfoil Data; Axial Flow Track Design; Multi-staging of compressor characteristics; Transonic Compressors; Shock Structure Models in Transonic Blades; Transonic Compressor Characteristics; 3-D Blade shapes of Rotors and Stators; Instability in Axial Compressors; Loss of Pressure Rise; Loss of Stability Margin; Noise problems in Axial Compressors and Fans

Course outline

- **Axial flow turbines** : Turbine stage; Turbine Blade 2-D analysis ; Work Done and Degree of Reaction; Losses and Efficiency; Flow Passage and flow track in multi-stage turbines; Subsonic, Transonic and Supersonic turbines; Multi-staging of Turbine; Exit flow conditions; Turbine blade cooling; Turbine Blade design – Turbine Profiles ; Airfoil Data and Profile construction;3-D blade design

Course outline

- **Centrifugal Compressors :** Introduction; Elements of centrifugal compressor/ fan; Inlet Duct ; Impeller flow; Effect of Slip factor; Concept of Rothalpy; Ideal and real work done; Incidence and lag angles; Diffuser ; Centrifugal Compressor Characteristics ; Surging and Rotating stall; Design variants of modern centrifugal compressors
- **Radial Turbine:** Introduction; Thermodynamics and Aerodynamics of radial turbines; Radial Turbine Characteristics; Losses and efficiency; Design of radial turbine
- **Use of CFD for Turbomachinery analysis and design**

Text/References

- Nicholas Cumpsty, *Compressor Aerodynamics*, 2004, Kreiger Publications, USA
- Johnson I.A., Bullock R.O. *NASA-SP-36*, *Axial Flow Compressors*, 2002 (re-release), NTIS, USA.
- NASA-SP-290, *Axial Flow turbines*, 2002 (re-release), NTIS, USA.
- NASA-SP-36, *Axial Flow Compressors and Fans, NTIS, USA*
- J H Horlock, *Axial flow compressors*, Butterworths, 1958, UK
- J H Horlock, *Axial Flow Turbines*, Butterworths, 1965, UK
- B Lakshminarayana; *Fluid Mechanics and Heat Transfer in turbomachinery,* 1995, USA

Text/References

- Dixon, S.L., Fluid Mechanics and Thermodynamics of Turbomachinery, 1998, Elsevier Publications

- Cohen, Rogers and Saravanamuttoo, Gas Turbine Theory, Prentice Hall, 2005

Evaluation scheme

- Quizzes (4): 10% (averaged)
  - No make-up for missed quizzes
  - Dates to be announced in advance, usually the next lecture following a tutorial),
  - Quizzes to be open note, open book.
- Course project: 15% (team of max 2 students)
- Mid-semester exam: 30%
- End-semester exam: 45%
- Mid-semester and end-semester exam: One A4 formulae sheet permitted
- Assignments/homework: After each tutorial session, exercise questions to be uploaded on moodle. These questions are meant for practice.

- Attendance not mandatory: No DX grade
  - Attendance to be recorded

Grading scheme:

- Total marks obtained during the semester to be added up and scaled to 100.
- The maximum marks scored (by the topper of the class) out of 100 to be converted to 100 (if the absolute marks scored is > 90) and marks of others to be normalized based on this scaling factor.
- If the maximum absolute marks scored is between 80-90, then the maximum grade awarded will be AB (The marks will be scaled to 95).

- **Cut-offs after normalization:**

  FR<40

  40<DD<45

  45<CD<55

  55<CC<65

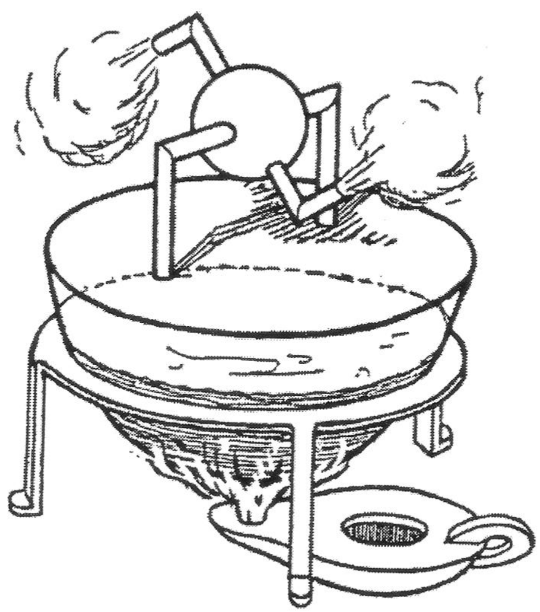
  65<BC<75

  75<BB<85

  85<AB<95

  95<AA<100

Hero's Aeolepile (2nd BC)



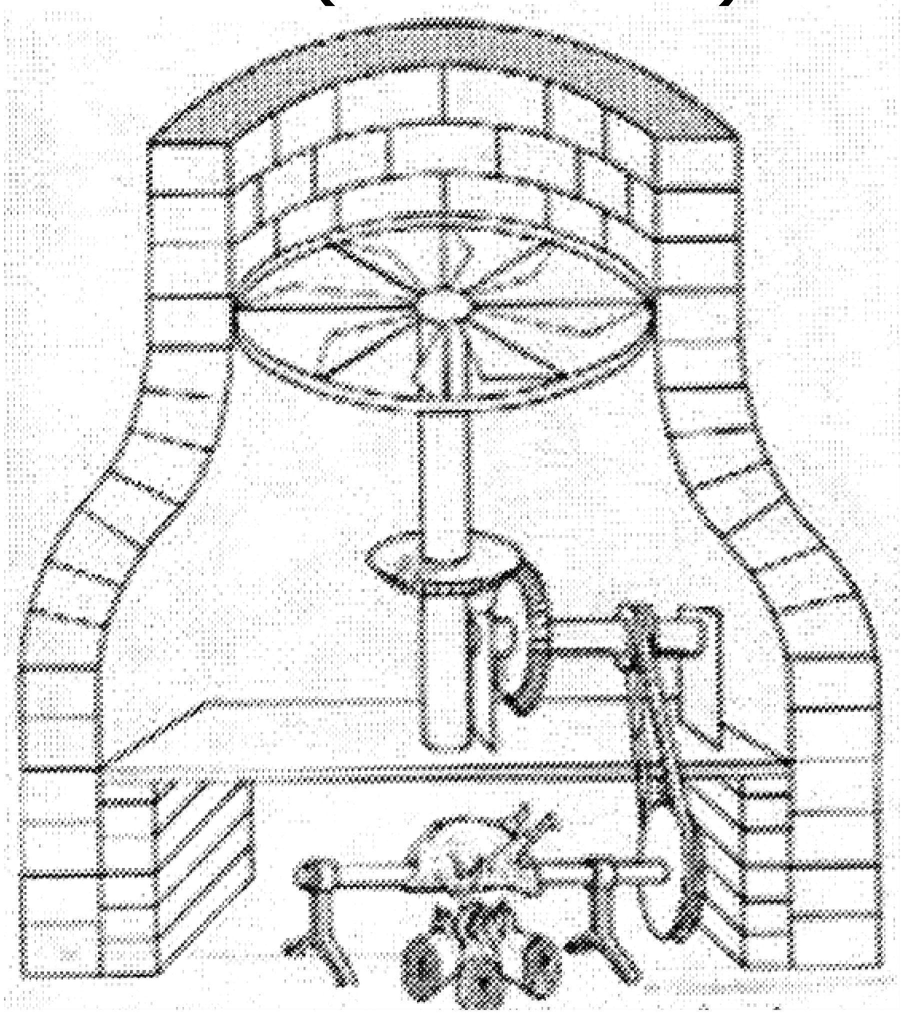
William Avery (1830)

Wan Hu’s Rocket (13th AD)

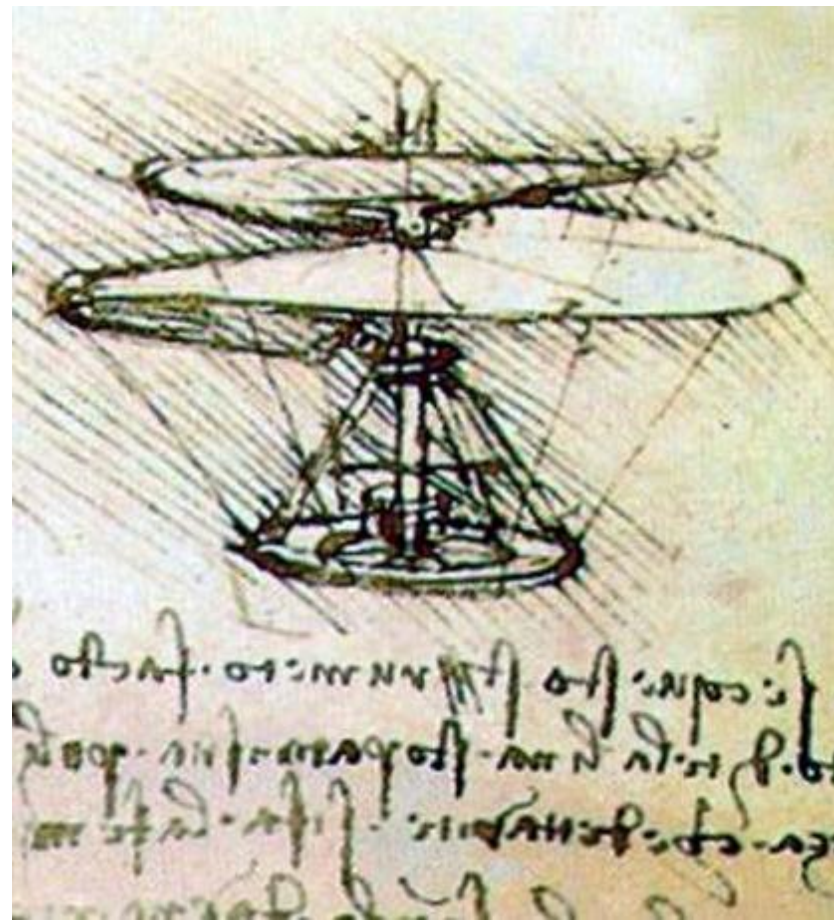
Multiple Rockets

Rocket Jets

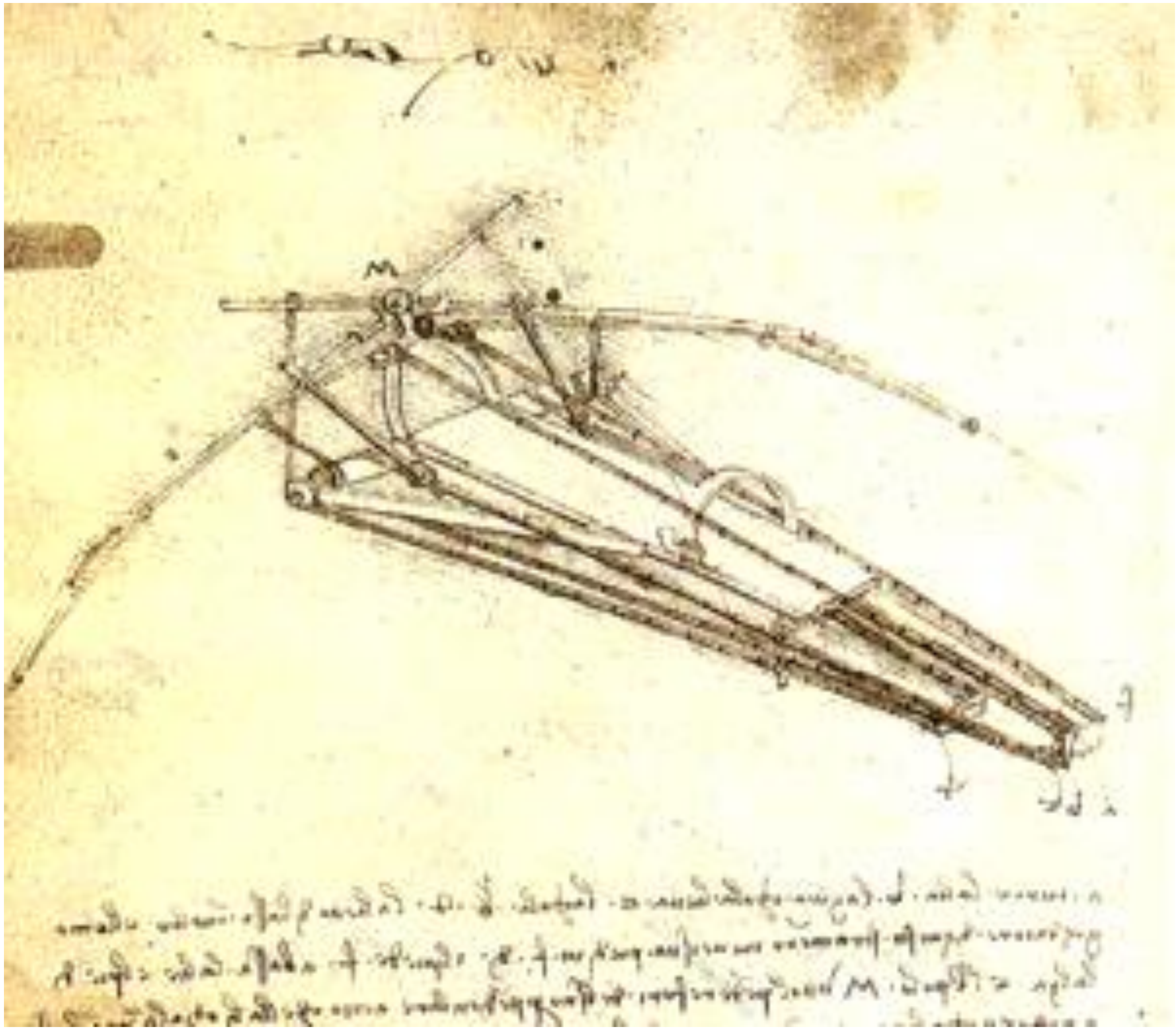
Da Vinci’s Chimney Jack (1500 AD)



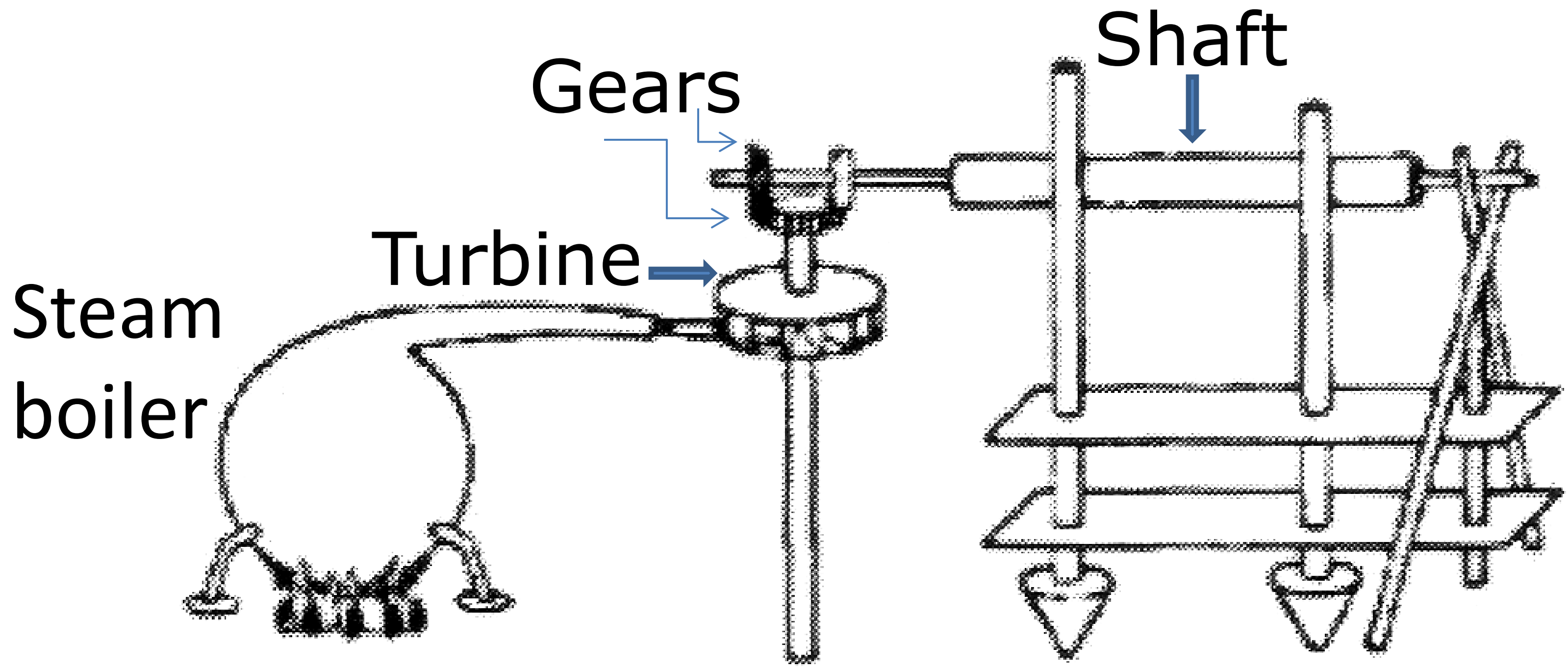
Da Vinci’ Ornithopter



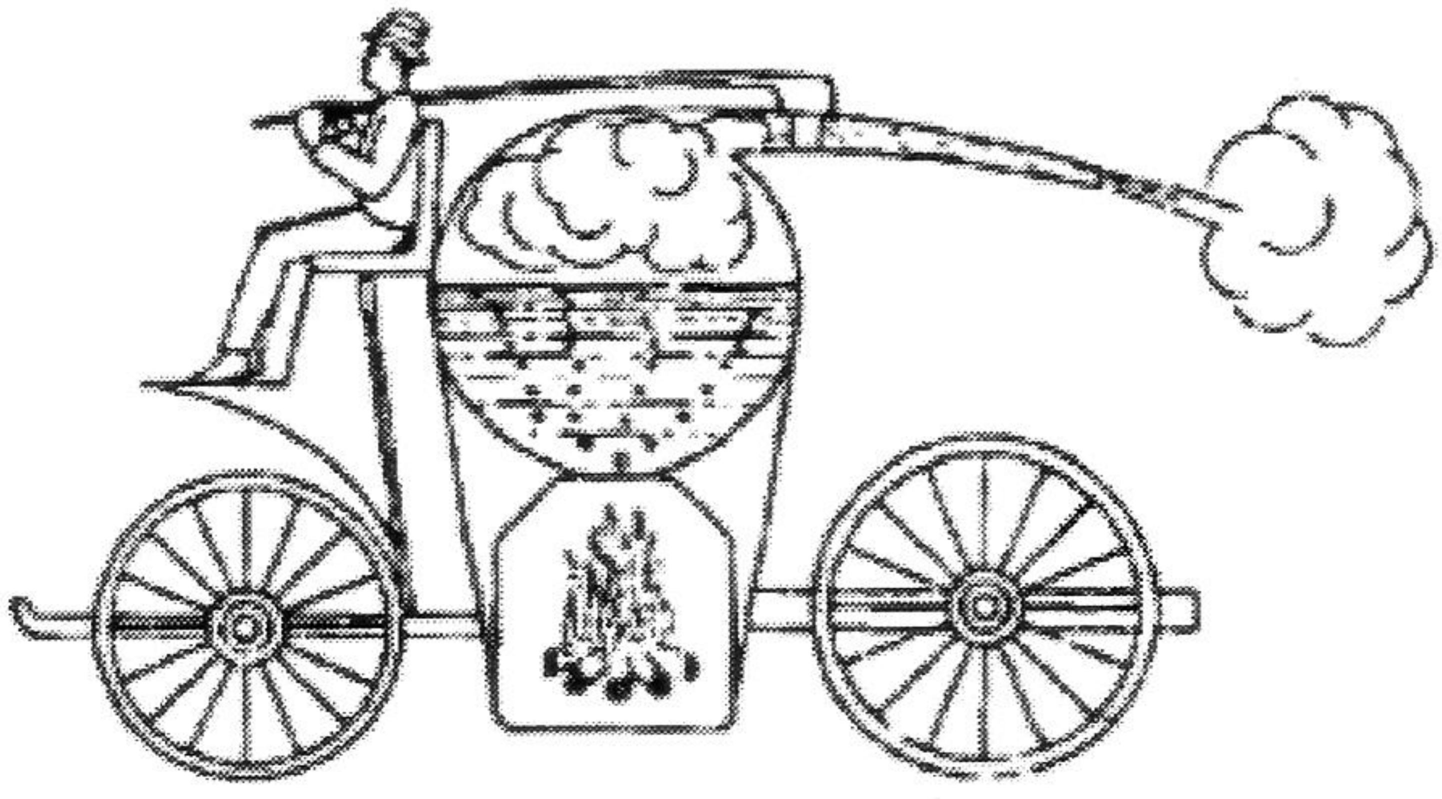
Da Vinci’s Flapping Wing Concept



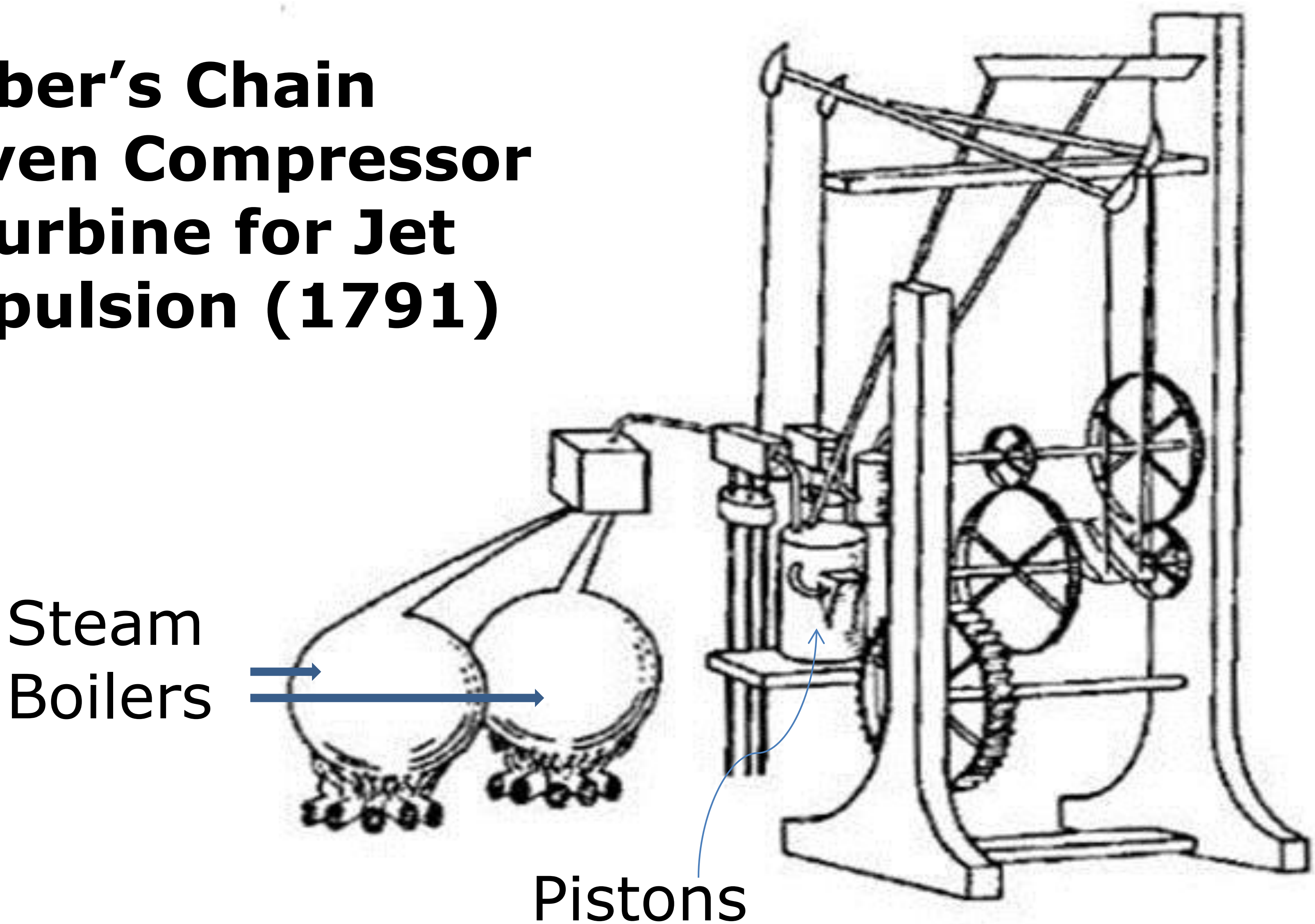
Giovanni Branca's Jet Turbine (1629)

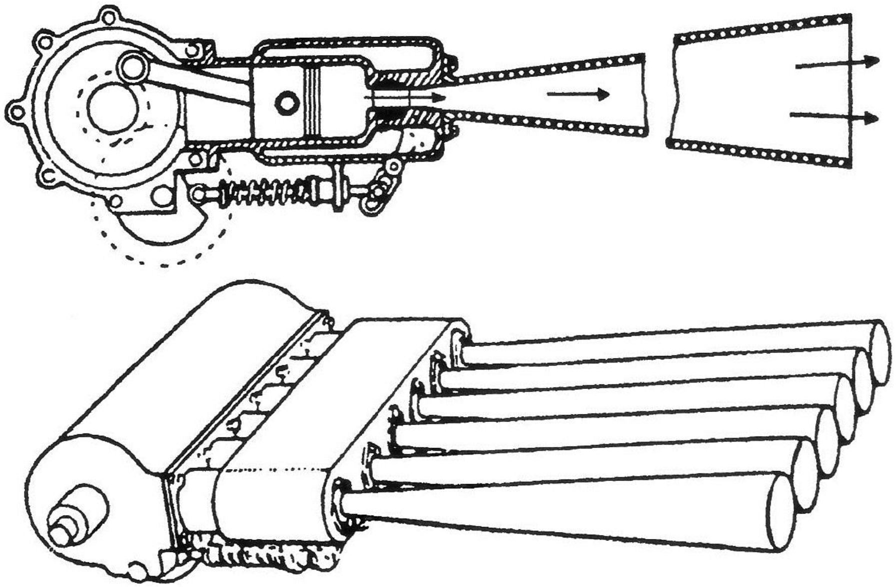


Newton’s Steam Wagon

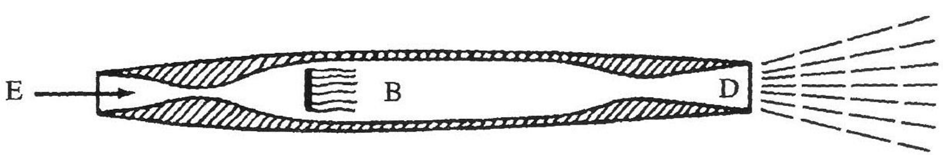


Barber's Chain Driven Compressor + Turbine for Jet propulsion (1791)



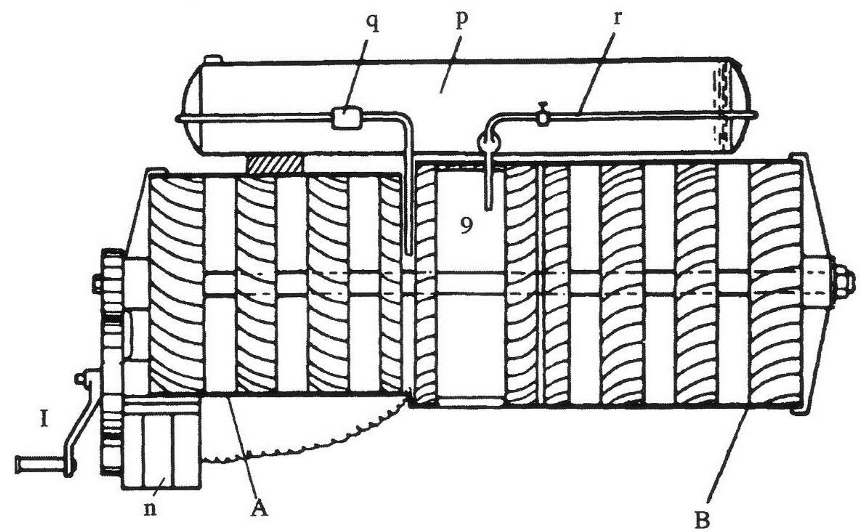


Lorin's 1908 patent.



Lorin's 1913 patent.

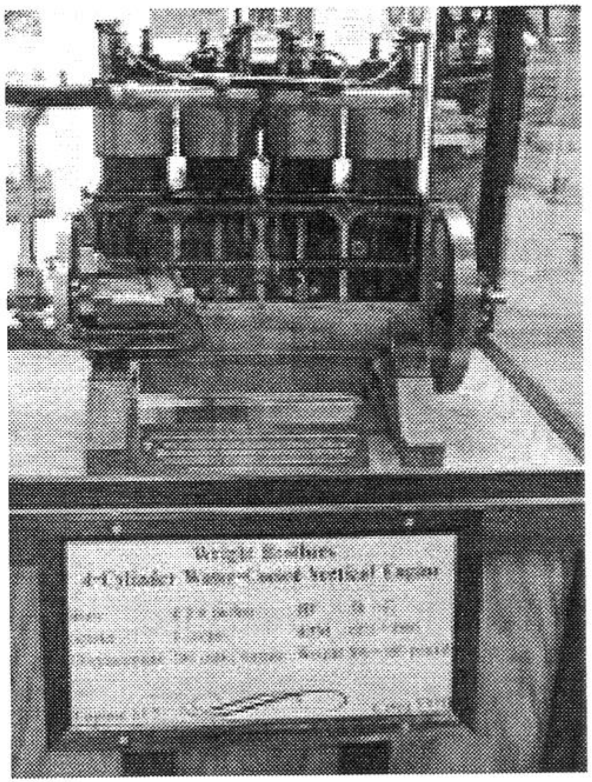
Lorin's Patent Drawings

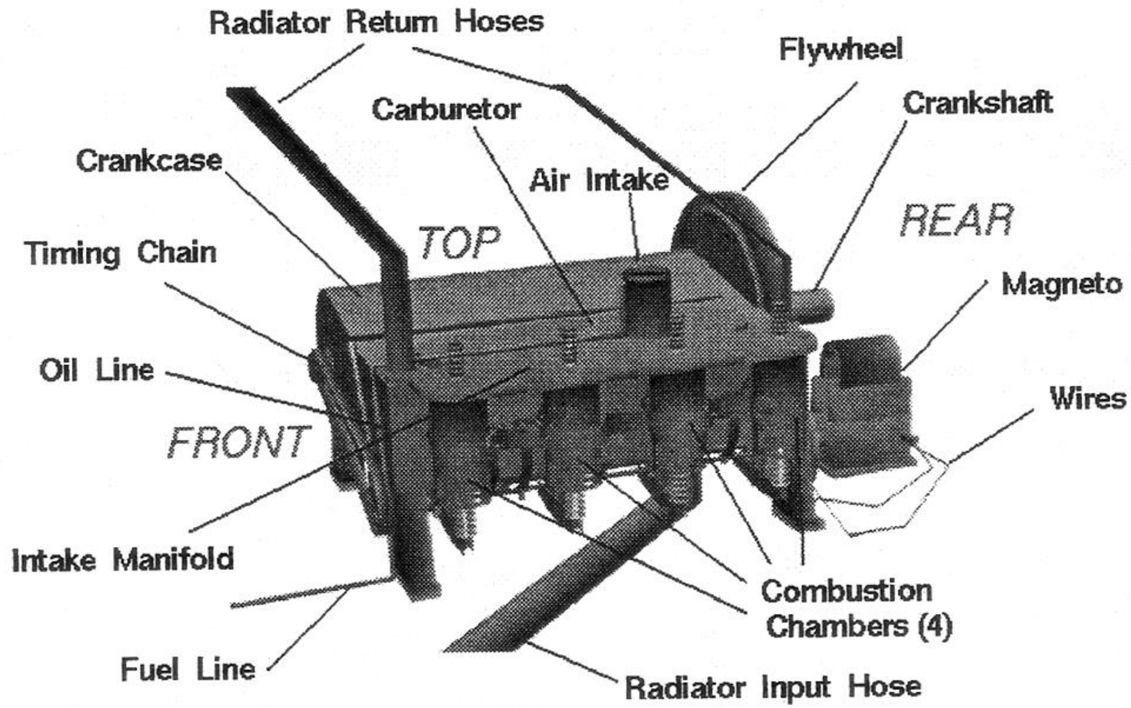


1921 Guillaume patent.

Guillaume's Patent of a Jet Engine

Wrights’ engine





First Flight 1903 Dec

Examples of gas turbine applications

Military aircraft (Low bypass Turbofan)

Civil aircraft (High bypass Turbofan)

Turboprop

Marine propulsion gas turbine

Land based gas turbine powerplant

APUs in civil aircraft

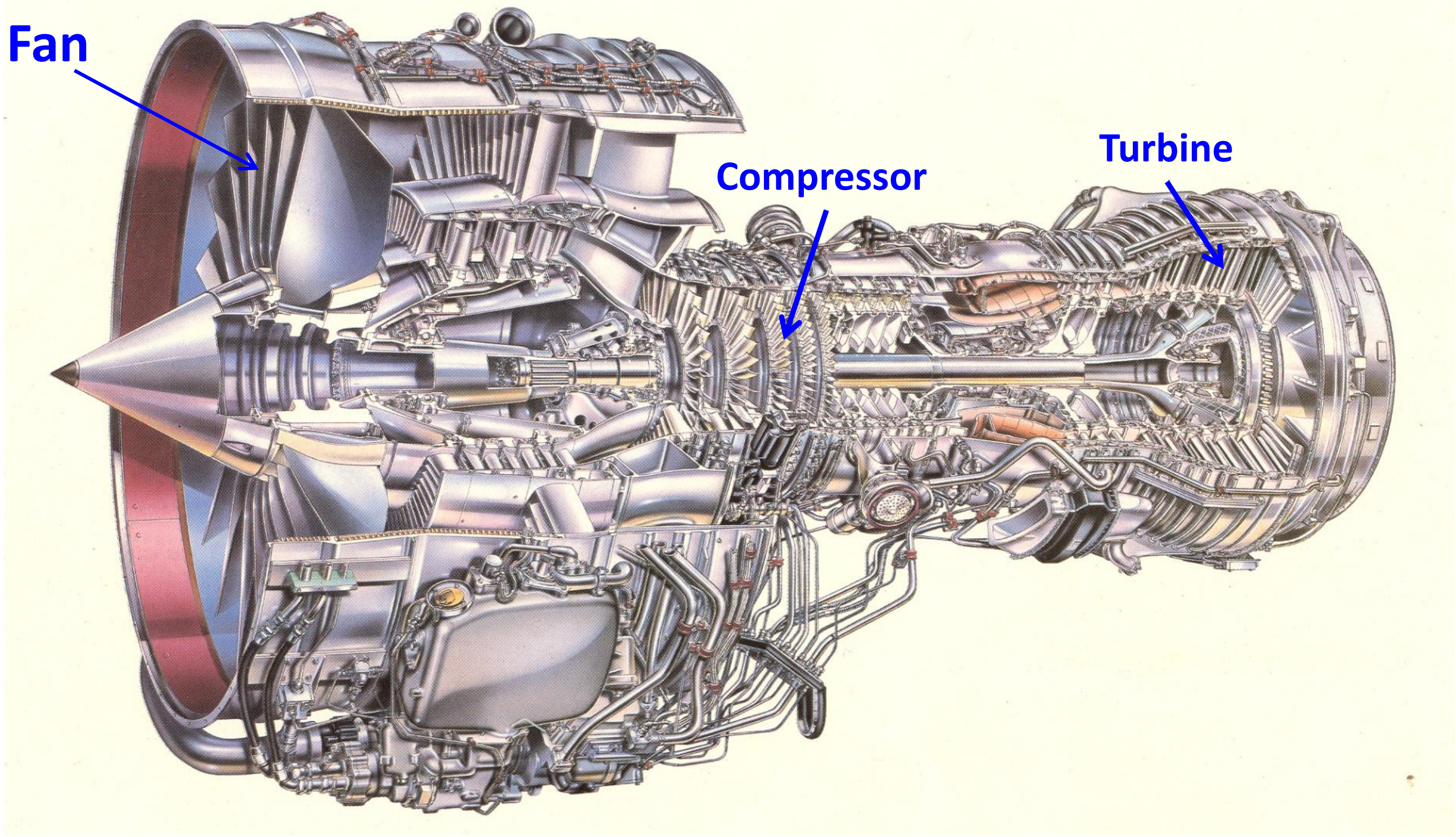
Turbopump for liquid
rocket propulsion

Modern / futuristic aircraft engines

Civil aircraft (High bypass Turbofan) B-787

Un-ducted aft-fan engine

Micro gas turbine



A modern high bypass turbofan engine

	787 Engines: GEnx-1B Trent 1000	767 Engines: GE CF6-80C2 RR RB211-524G/H
Bypass Ratio	~10	~5
Overall Pressure Ratio	~50	~33
Thrust Class	53,000–74,000 lbf	53,000–63,000 lbf
Fan Diameter	111–112 in	86–93 in
Specific Fuel Consumption	15% lower	Base
Noise	ICAO Chapter 4	ICAO Chapter 3
Emissions	CAEP/8 (2014)	CAEP/2

Source: http://www.boeing.com/commercial/aeromagazine/articles/2012_q3/2/