AVDASI 3
(CADE 30007)
Gas Turbine Performance

Week 13: Lecture 1

Introduction to Gas turbine & ISA

Lecturer:

Dr Daniele Zagaglia

daniele.zagaglia@bristol.ac.uk

Unit Director:

Dr. Samudra Dasgupta

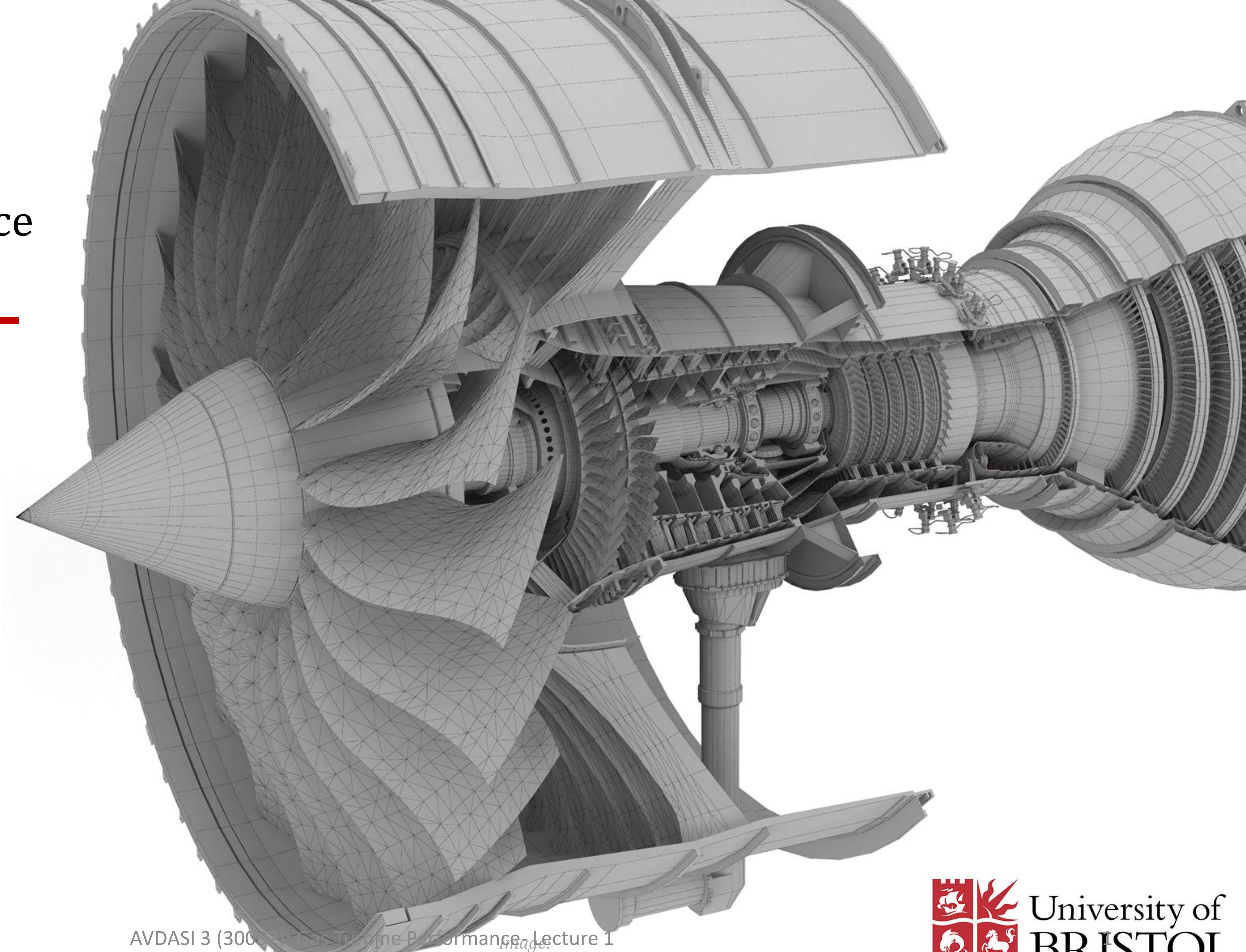


Image: https://www.cgtrader.com/3d-models

University of BRISTOL

Learning Objectives for Lecture 1

- Introduce the topic
- Detail Useful textbooks
- Outline of the units and nomenclature
- Describe the possible engineering units
- Understand how thrust is produced in a jet engine
- Introduction to the Joule-Brayton cylcle
- Example of Aiframe/Engine combination
- Understand the International Standard Atmosphere

Learning Objectives of the Unit

University of BRISTOL

- **Objectives**
  - *To describe the basic features of aircraft propulsion, engine performance and design.*
- **Learning Outcomes**
  - *On successful completion of the unit the student will have an introductory knowledge of the propulsion concepts used in aircraft and be able to apply this knowledge to set problems.*
- **Prerequisites**
  - *Engineering Science A/B*
  - *Fundamentals of Aerodynamics*
- **Assessment**
  - *100% Timed Assessment at end of Teaching Block 2*

Major Themes

University of BRISTOL

- Introduction
- Performance – basic cycle
- Integration of the Engine in Airframe
- Turbomachinery – Compressors & Turbines
- Combustion & Control of Engine behaviour

Lectures & Text Books

The full set of recorded lectures & the lecture slides can be found on Blackboard. This material is aimed at providing the basic information necessary to fulfil the overall learning objectives and should be amplified with your own notes. Students should refer to textbooks for a fuller description and for further background reading.

- **Recommended:**

  Gas Turbine Theory ***Saravanamuttoo, Rogers, Cohen & Straznicky***
  Pearson 3rd , 4th , 5th or 6th Edition

- **Other Titles:**

  Fundamentals of Jet Propulsion with applications ***Flack*** ***Cambridge***

  Jet Propulsion ***Cumpsty & Heyes*** ***Cambridge University Press***

  Aircraft Propulsion & Gas Turbine Engines ***Ahmed F. El-Sayed*** ***CRC Press***

  Gas Turbine Performance ***Walsh & Fletcher*** ***Blackwell Science***

Units

Basic Units:	**Preferred SI**	**Imperial**
(Mass, length, time & temperature)		
Mass	kg	slug
Length	m	ft
Time	s	s
Temperature	C/K	(F/R)

Derived units:

Force	Newton N or Kilonewton kN	lbf
Pressure	Kilopascal kN/m2 or kPa	lb/in2
Work or Energy	Kilojoule kJ or kNm	ft lb
Power	Kilowatt kW or kJ/s	hp

Symbols

Mass Flow	$\dot{m}$	kg/s
Thrust / Force	F	kN
Absolute Velocity	C	m/s
Relative Velocity	V	m/s
Mach Number	M	
Total Temperature	T_o	C/K
Static Temperature	T	C/K
Total Pressure	P_o	kPa / bar
Static Pressure	P	kPa / bar
Work / Energy	W	kJ
Power	P_{ow}	kW

Subscripts/Superscripts

a	ambient
‘	Ideal
N	at nozzle throat
N^*	static conditions @ nozzle throat
c	Bypass flow
h	LP turbine exit flow
j	Mixed flow at jet exit

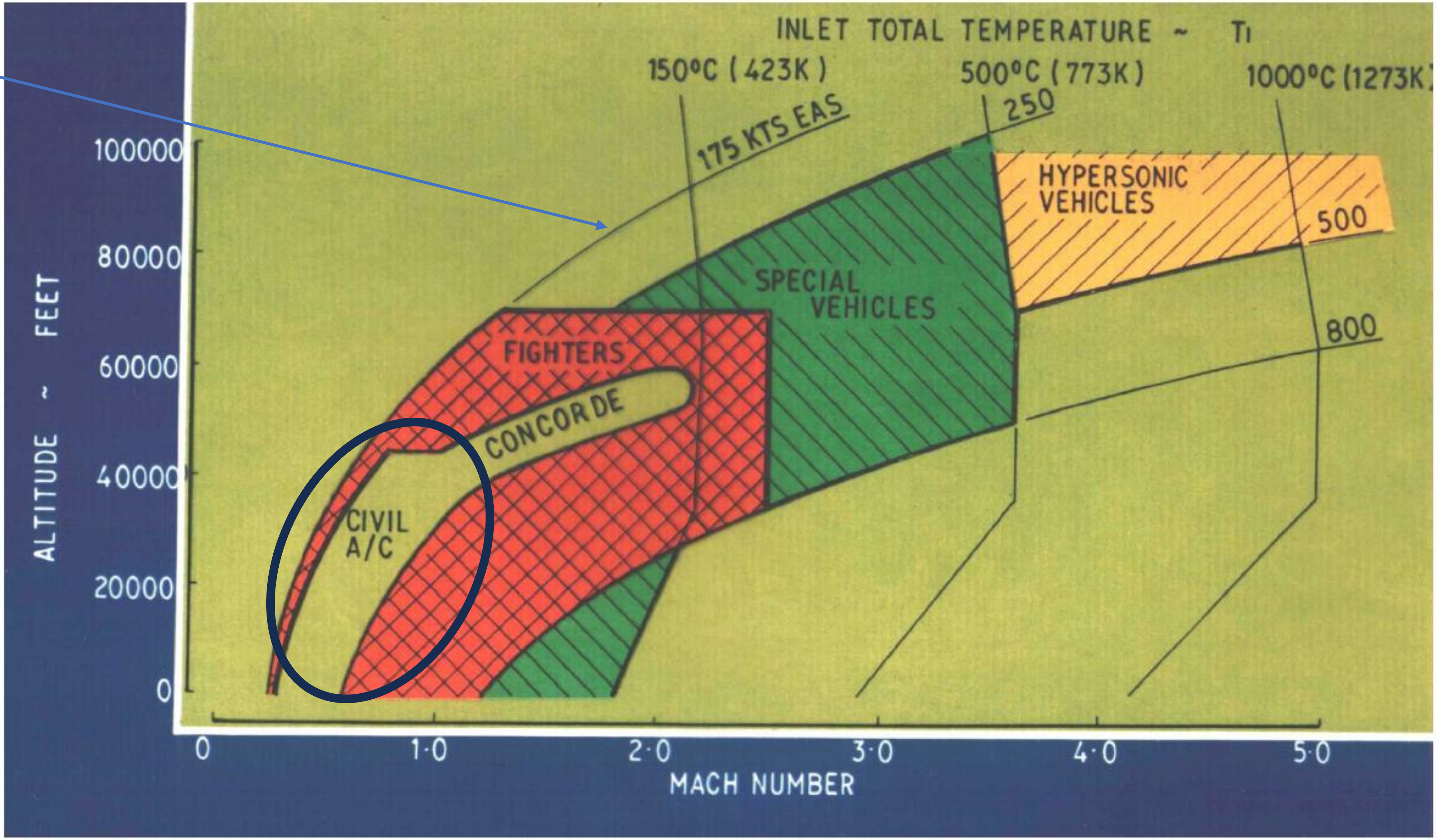
Altitude vs Mach Number

Lines of constant dynamic pressure

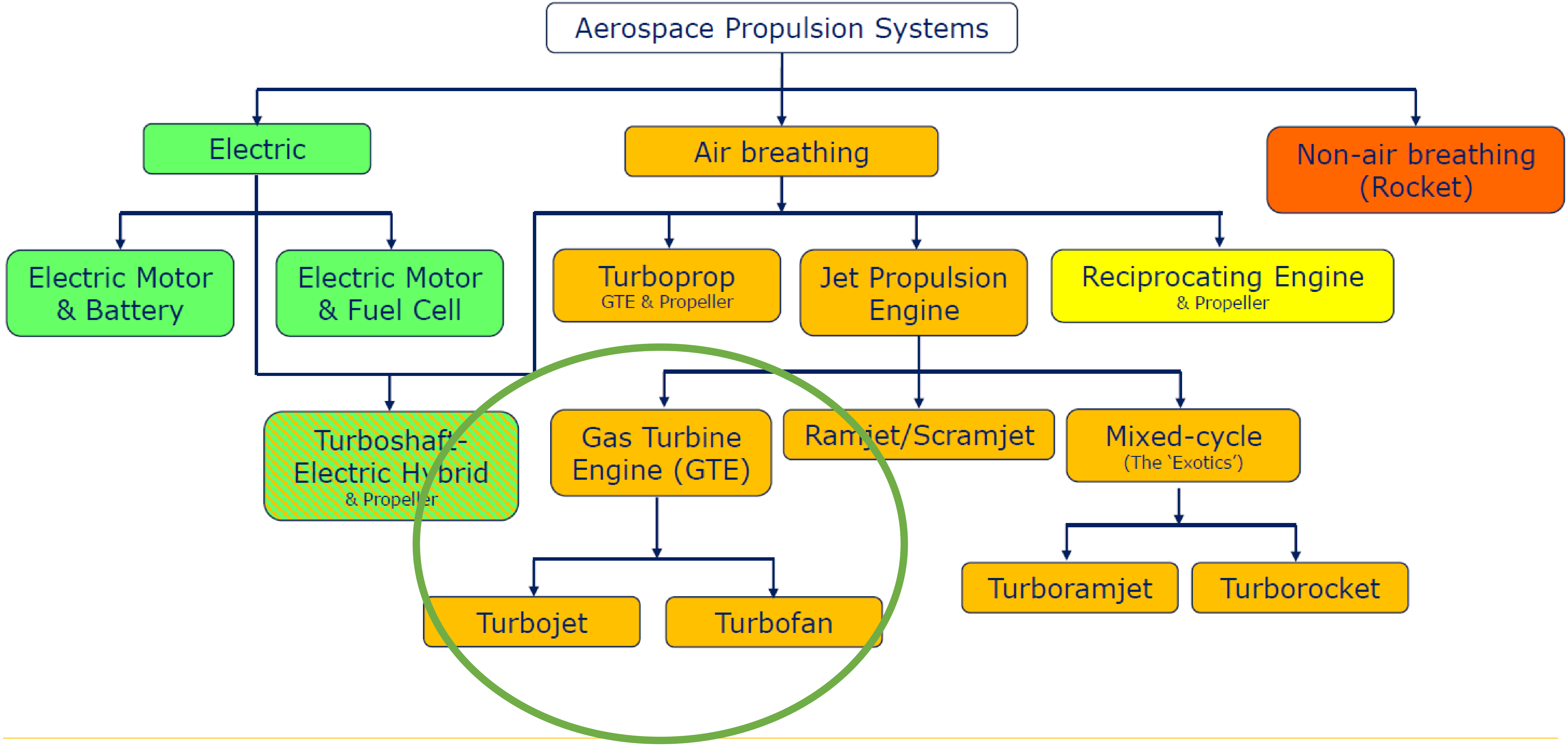
$$\frac{1}{2}\rho V_{TAS}^2 = \frac{1}{2}\rho_{SL} V_{EAS}^2$$

$$V_{TAS} = V_{EAS}\sqrt{\frac{\rho_{SL}}{\rho}}$$

$$W = L = \frac{1}{2}\rho V_{TAS}^2 S C_L$$



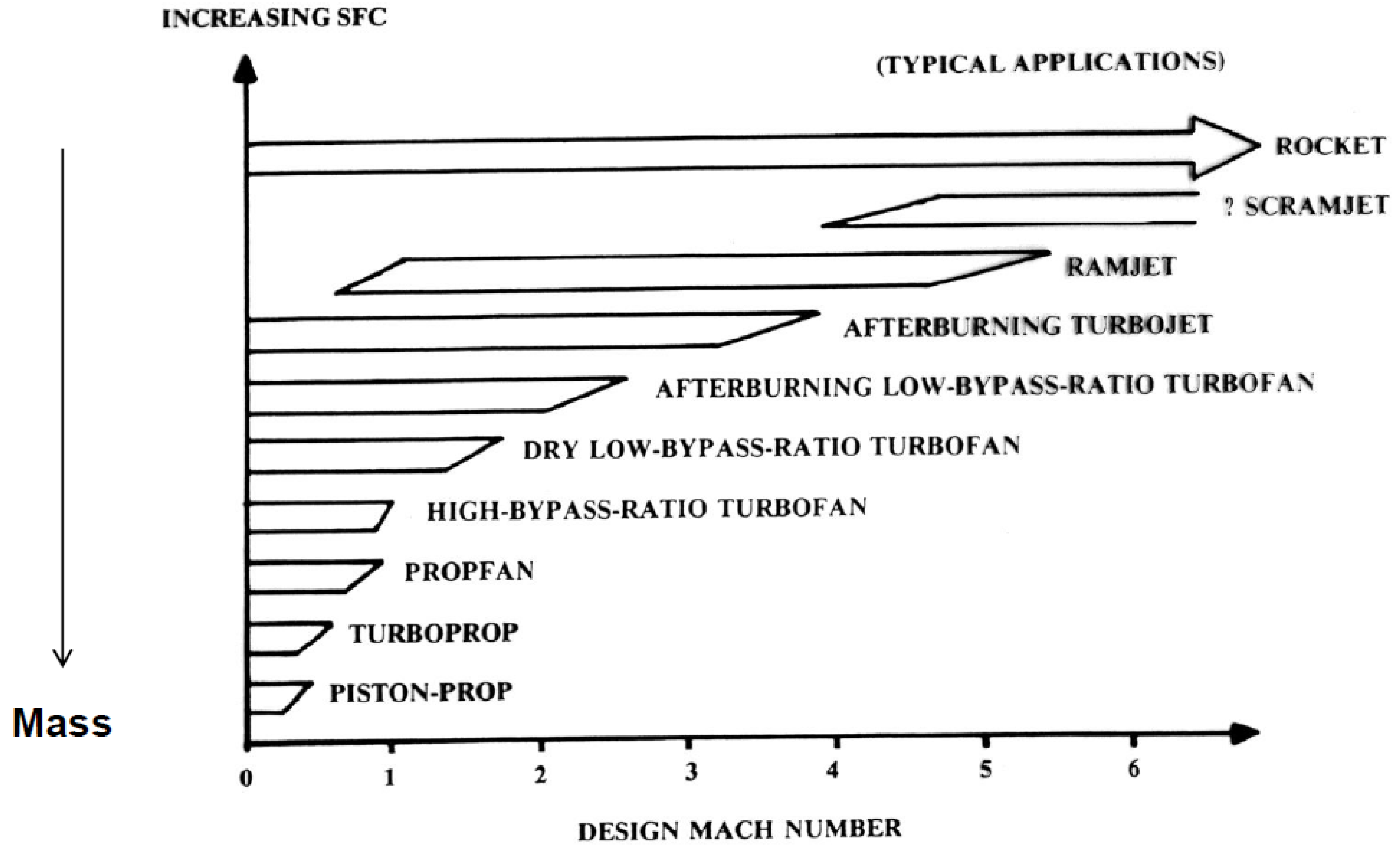
Propulsion System Classification



Choice of Propulsion System

Specific Fuel Consumption ~ Fuel flow per unit thrust ~ kg/hr/N or lb/hr/Lb

Increasing SFC leads to lower efficiency



What is thermodynamics?

- **Thermodynamics -** the interrelationship and the conversion of different forms of energy

- **Energy -** the potential capacity to do work

- ***For Example***
  - Gravitational energy (weight driven clock escapement)
  - Kinetic energy
  - Elastic energy
  - **Energy stored in a Hydrocarbon Fuel**
  - **Heat - the transmission of energy by temperature difference**
  - **Electrical energy**
  - Nuclear energy
  - Mass as an energy source - $E = mc^2$

What relevance does it have to this course?

The turbojet engine – an energy converter

For analysis purposes the Propulsion Unit is stationary in a uniform flow field

Hydrocarbon energy into air

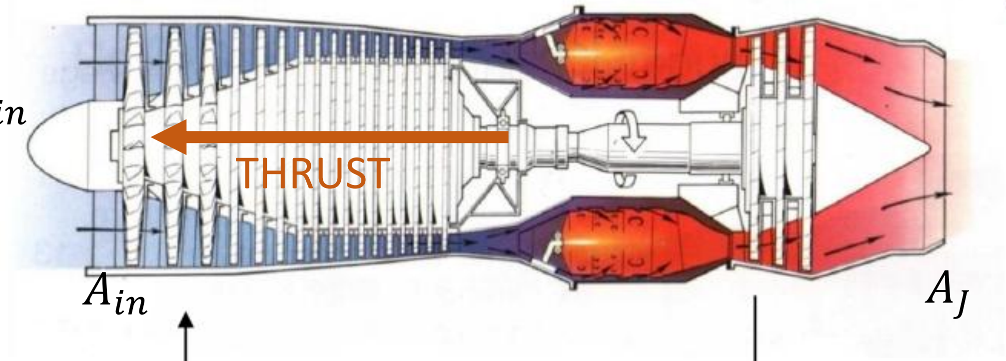
$\dot{m}_f$

Useful work in form of a jet

$\dot{m}_{in} = \rho_{in} A_{in} V_{in}$

V_{in}

P_a



$\dot{m}_j = \dot{m}_{in} + \dot{m}_f$

V_{out}

P_a

Work into air

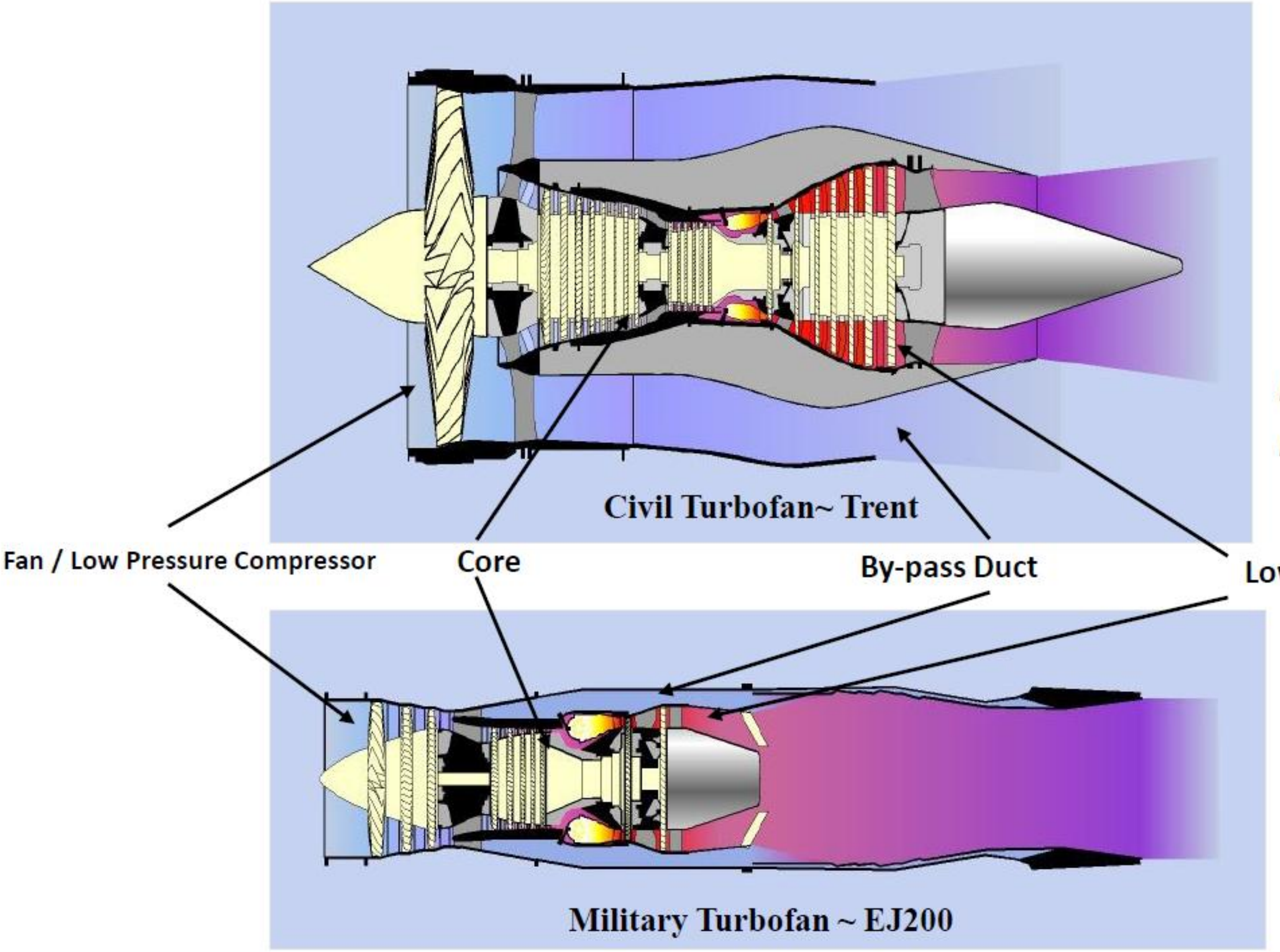
Extract thermal energy from air to produce power to drive compressor

Via shaft

$$Thrust \rightarrow F = (\dot{m}_j \cdot V_{out} - \dot{m}_{in} \cdot V_{in}) + A_J(P_j - P_a)$$

$$Propulsive\ Efficiency \rightarrow \eta_{prop} = \frac{2}{1 + \frac{V_{out}}{V_{in}}}$$

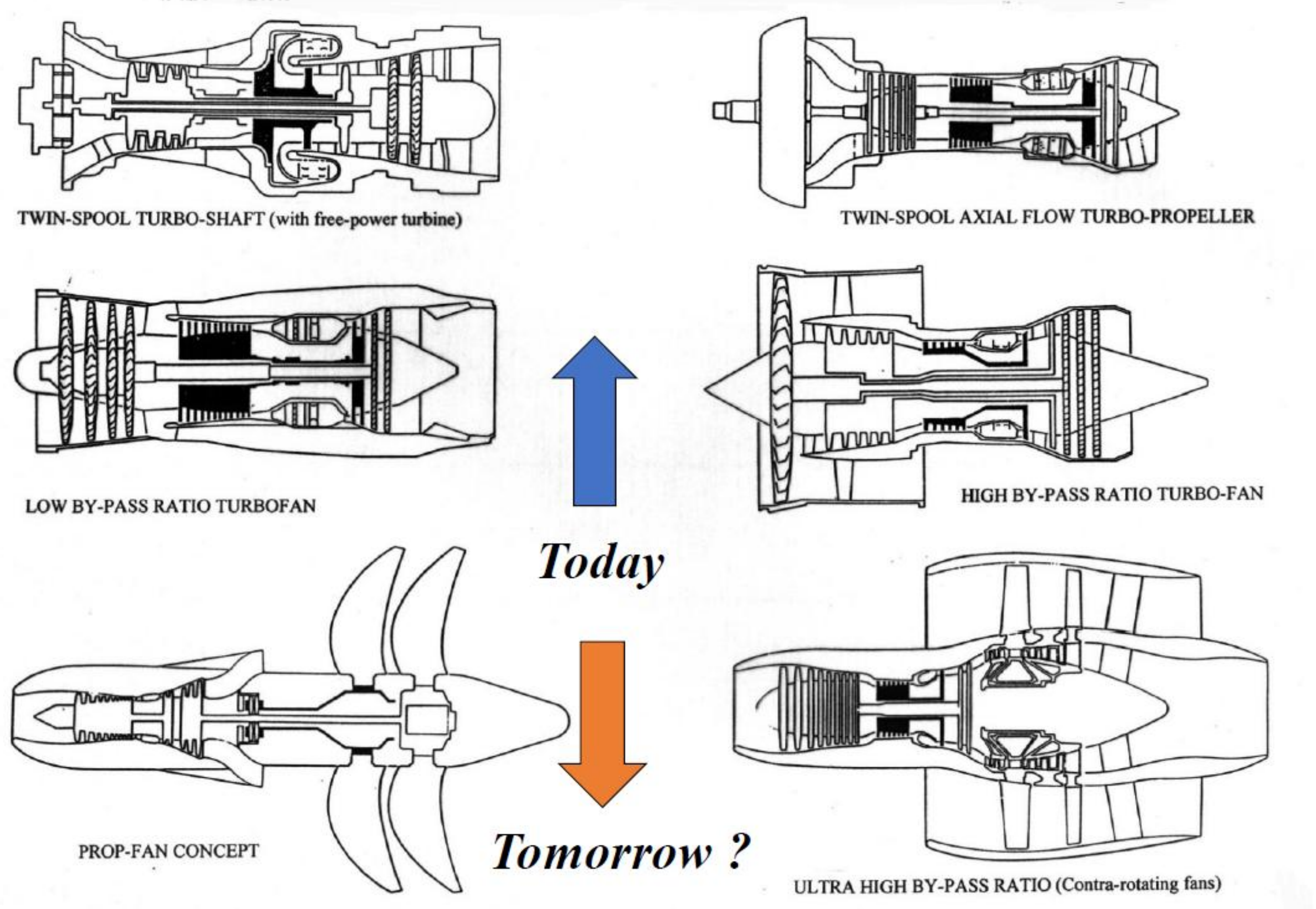
By-pass Turbofan



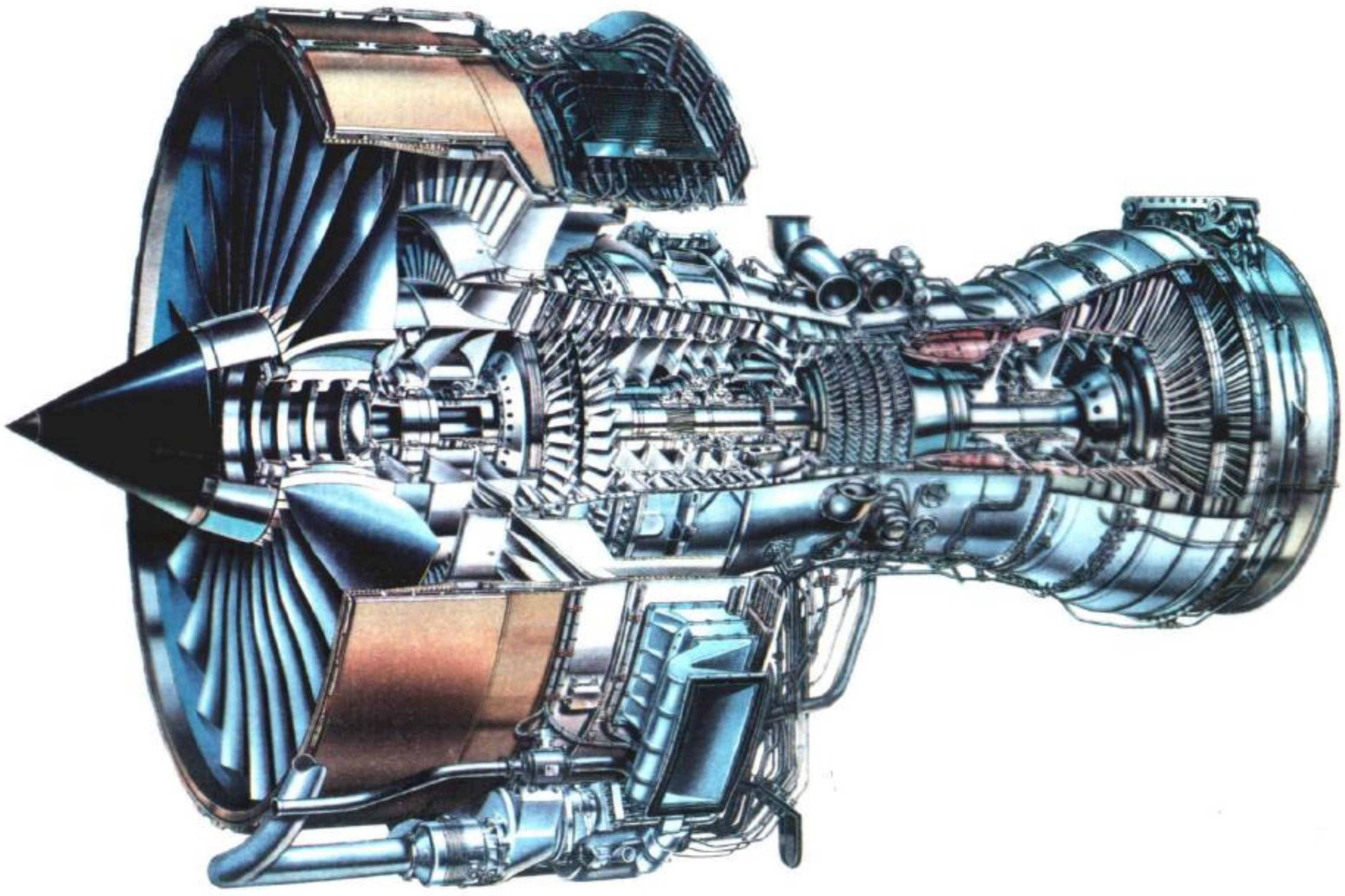
Bypass Ratio =

Flow in Duct/Flow in core

Mechanical arrangements of gas turbines



Rolls Royce Trent



Engine comparison

University of BRISTOL

		RB211	Trent 1000
Design era		**(1970's)**	**(2011 EIS)**
Aircraft		L1011	B787
Thrust	kN (Lb)	185 (43,000)	335 (75,000)
SFC * @ cruise	kg/hr/N	0.063	0.055
Mass	kg	4200	5400
Mass flow	kg/s	625	1210
Fan Diameter	m	2.15	2.85
Overall pressure ratio		25	52
By-pass ratio		5	11
Turbine Entry Temperature TET	K	1500	1800
Specific Thrust +	N/kg/s or m/s)	300	280
Thrust/Weight		5	6

* *SFC Specific Fuel Consumption at M=0.8 35,000 ft*

\+ *Specific Thrust = Thrust per unit mass flow (usually quoted at Sea Level Static).*

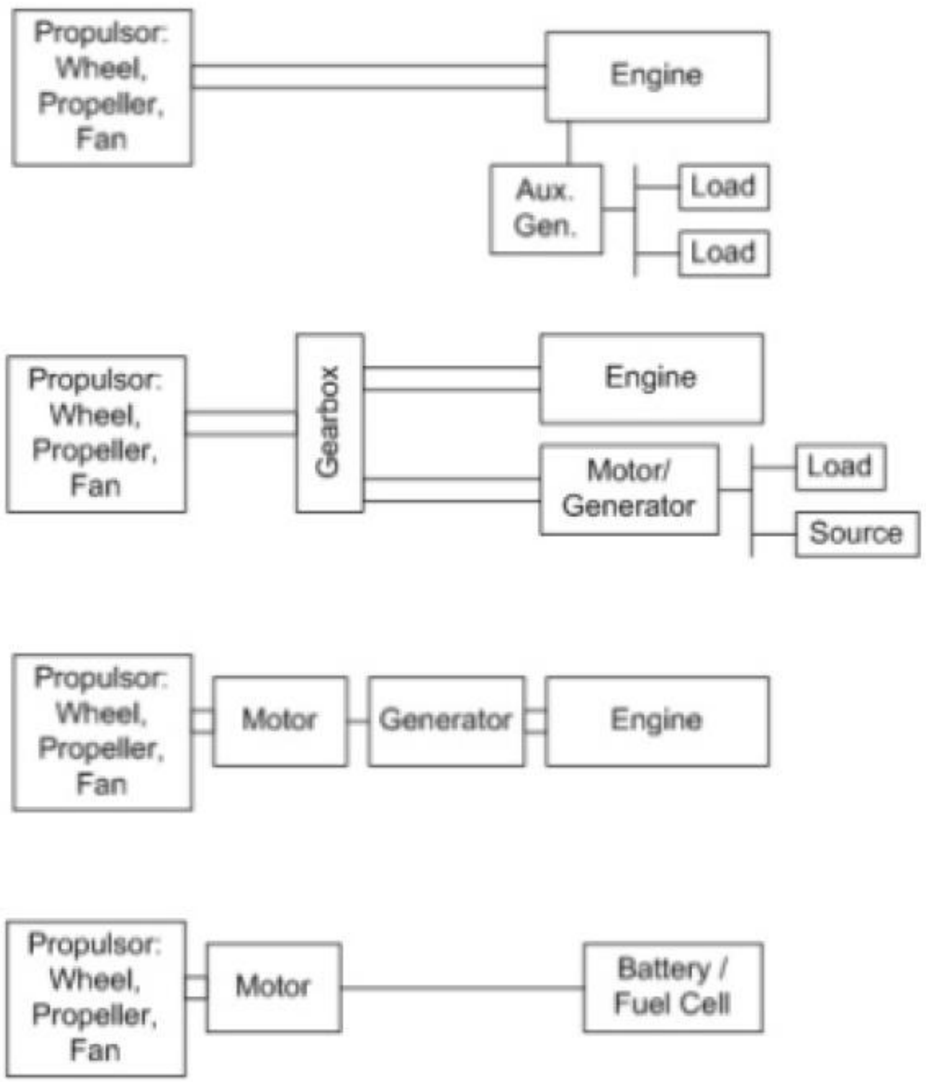
Hybrid and Electric propulsion: overview

Conventional:
Electrical system not propulsive

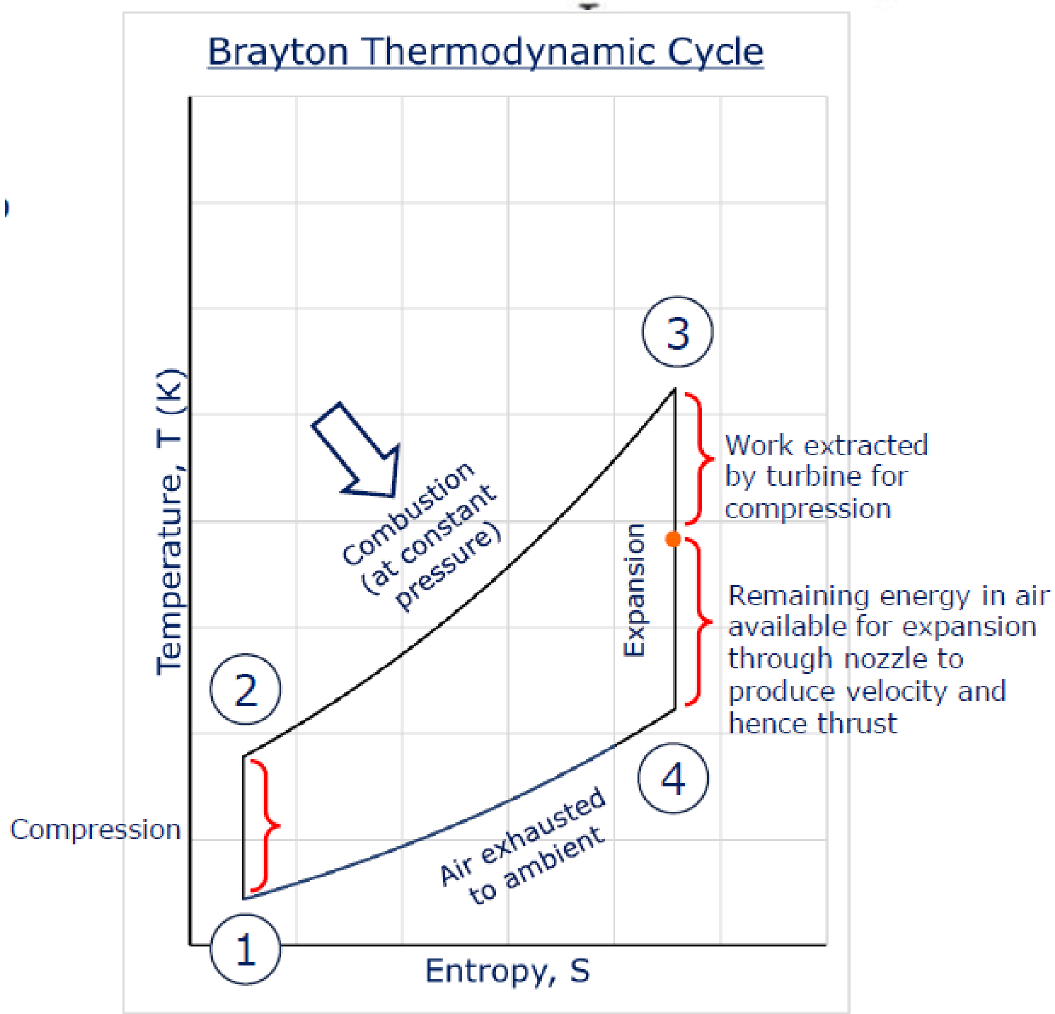
Hybrid Electric Propulsion:
Both engine and motor can directly drive the propulsor
- Also called a parallel hybrid
- May or may not have batteries

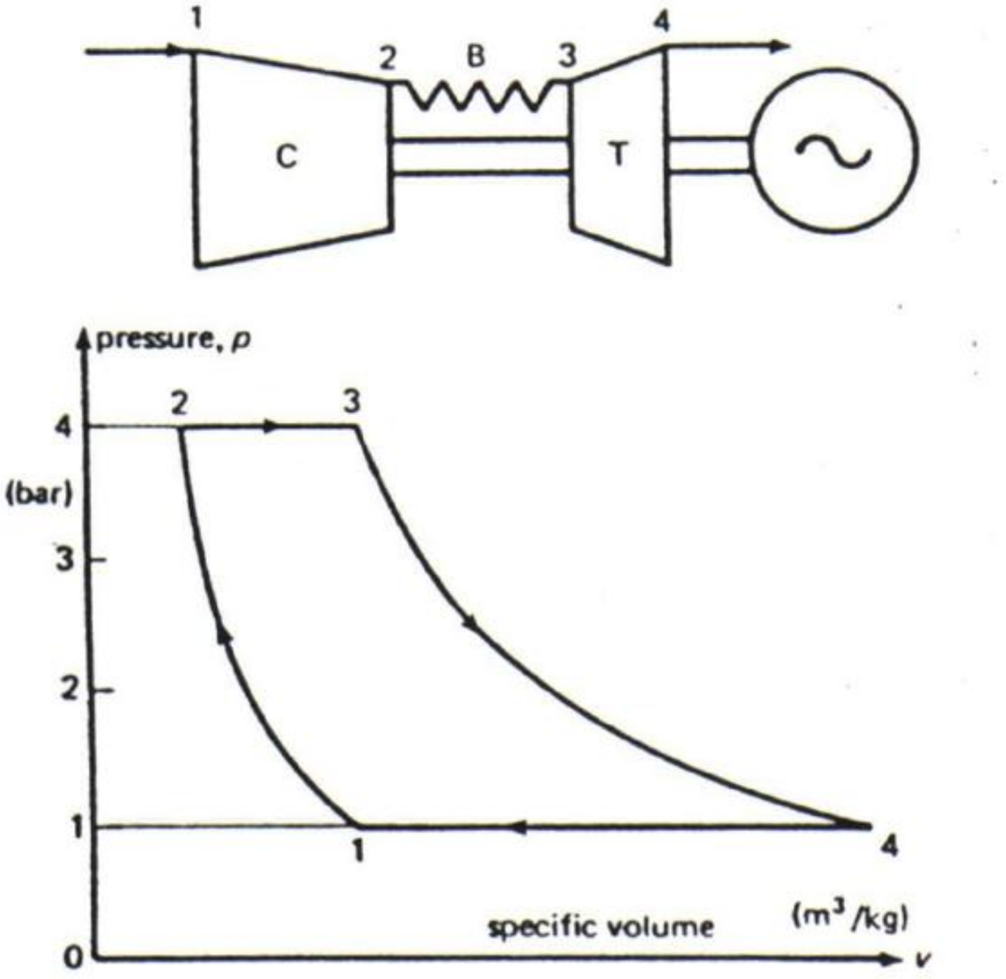
Diesel-Electric / Turbo-Electric Propulsion:
All propulsion power transmitted electrically from the engines
- Also called a series hybrid
- May or may not have batteries

Electric Propulsion: **No engines**



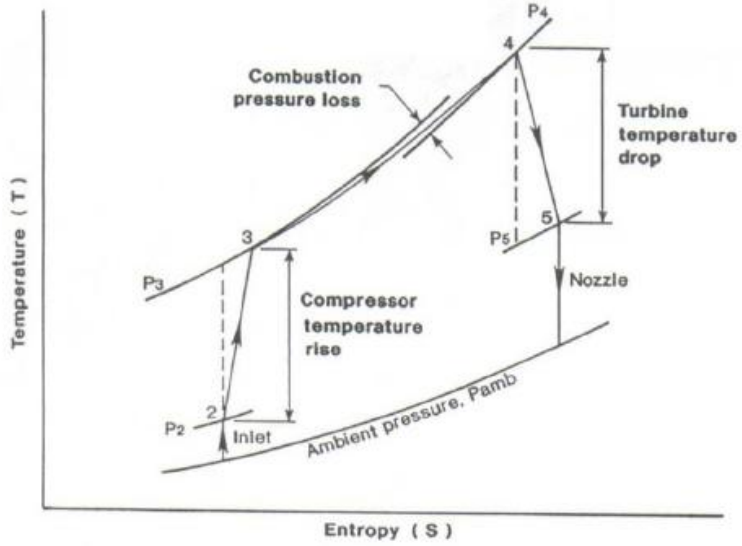
Joule or Brayton Cycle for a Gas Turbine

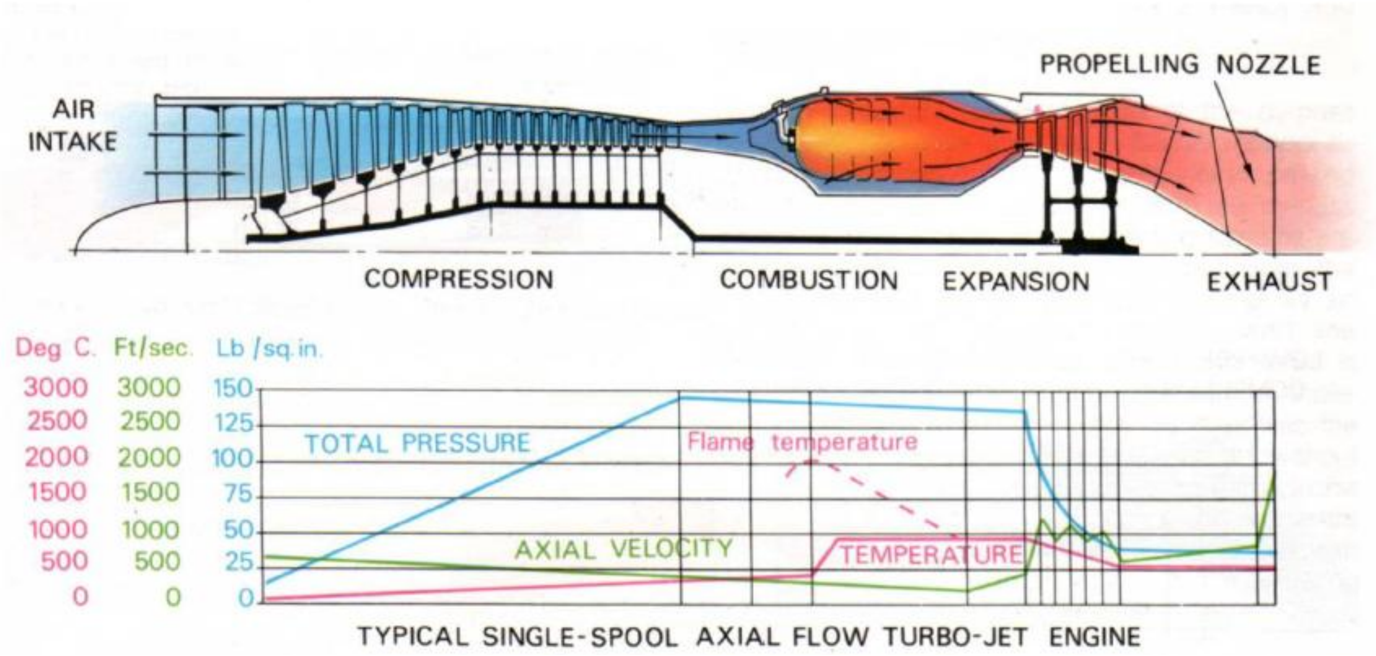




$$\eta = 1 - \{1/(p_2/p_1)\}^{\gamma - 1/\gamma}$$

The Practical Turbojet Cycle

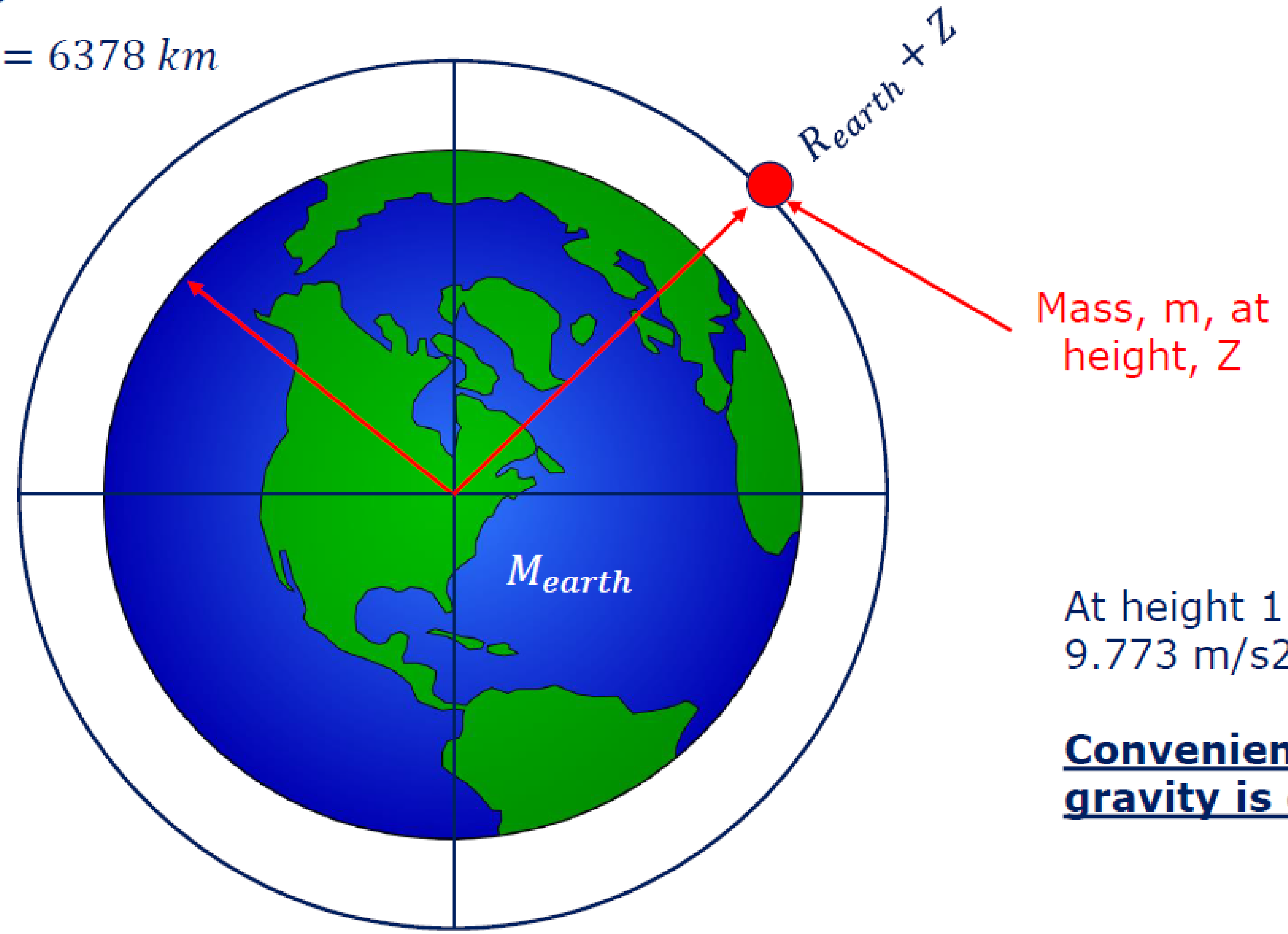




International Standard Atmosphere (ISA)

Average radius of earth is:

$R_{earth} = 6378\ km$



Acceleration due to gravity

Standard value: $g_{sl} = 9.80665\ m/s^2$

From:

$$F = \frac{G \times M_{earth} \times m}{(R_{earth} + Z)^2}$$

$$g_z = \frac{g_{sl} \times R_{earth}^2}{(R_{earth} + Z)^2}$$

At height 11000 km, acceleration due to gravity 9.773 m/s2 i.e. -0.4% from average sea-level value.

Convenient to assume acceleration due to gravity is constant with position and altitude.

International Standard Atmosphere (ISA)

University of BRISTOL

Altitudes

- Geometric height Z: The actual height above mean-sea-level.

- Geopotential height H: The height in a uniform gravitational field *(g constant with altitude)* which gives the same potential energy as exists in the actual, variable gravitational field.

$$h = \frac{R_{earth} Z}{R_{earth} + Z}$$

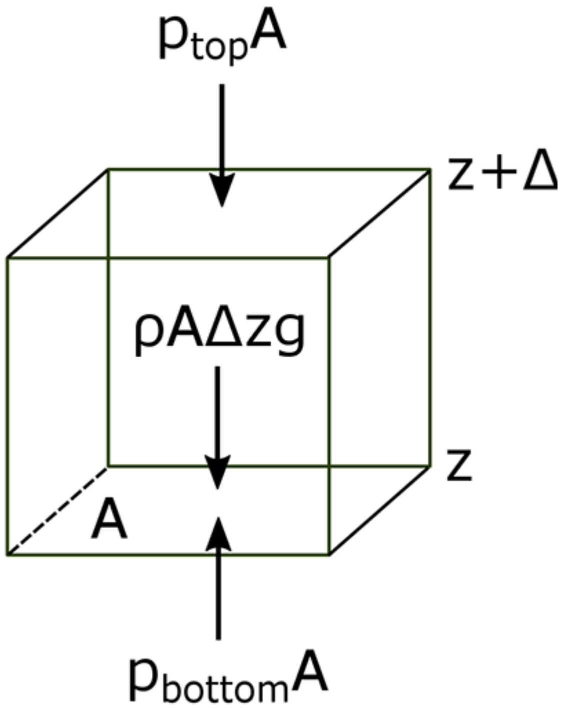
- Pressure height: Aircraft normally fly at altitudes defined by barometric means. The pressure height in any atmosphere is the geopotential height in the standard atmosphere giving the same pressure.

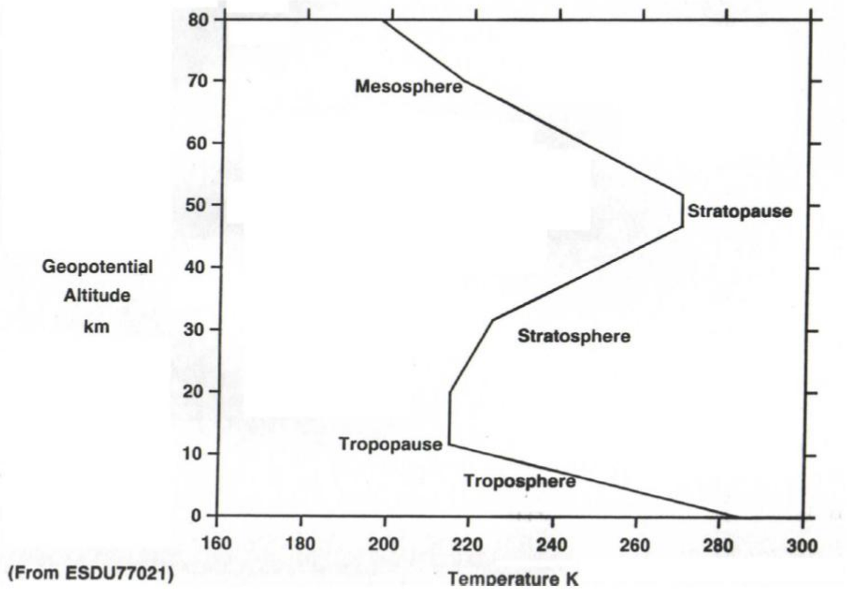
International Standard Atmosphere (ISA)

Hydrostatic Equilibrium:

$$\frac{dP}{dh} = -\rho(h)g = -\frac{P}{RT(h)}g$$

We need a model for the temperature variation with altitude to close the problem!





The international standard atmosphere is based on an idealised mean-annual, steady state model assuming a period of moderate solar activity and at alatitude of 45° N.

$P_{SL} = 101.325\ kPa$

$T_{SL} = 288.15$ K

$\rho_{SL} = 1.225\ kg/m^3$

In the troposphere, $T = T_{SL} - Lh, L = 0.0065\frac{K}{m}$

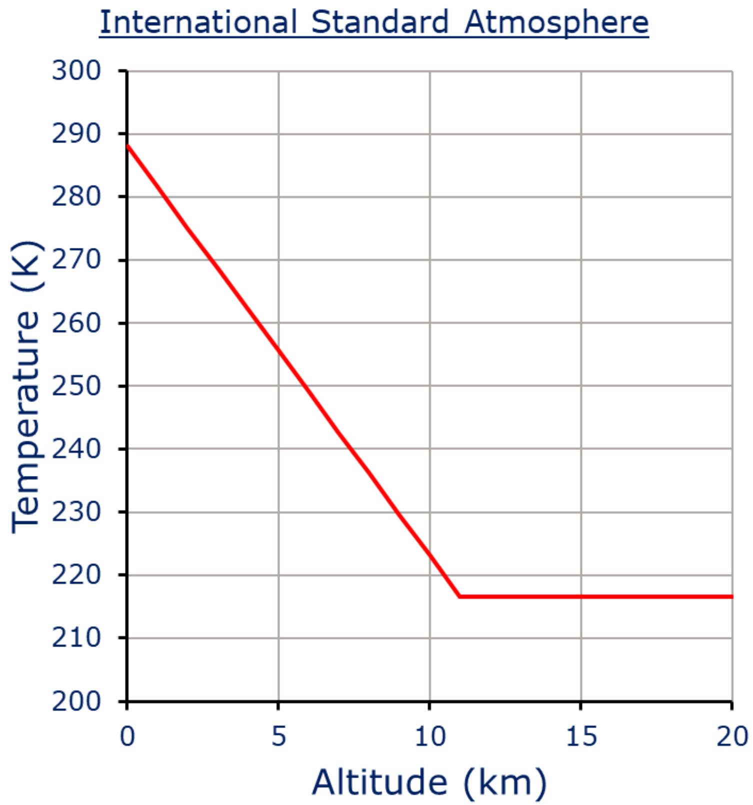
L is called L

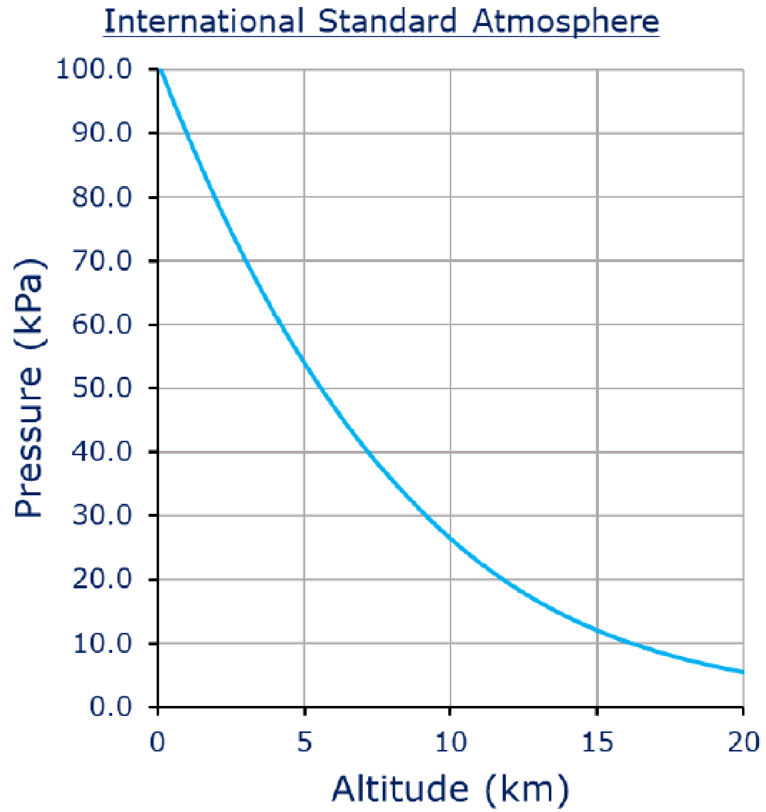
International Standard Atmosphere (ISA)

$$\frac{dP}{dh} = -\rho(h)g = -\frac{P}{RT(h)}g,$$
$$T(h) = T_{SL} - Lh, L = 0.065\ K/m$$

$$\frac{dP}{dh} = -\frac{P}{R(T_{SL}-Lh)}g$$
$$\frac{dP}{P} = -\frac{P}{R(T_{SL}-Lh)}g\ dh$$

$$\int_{P_{SL}}^{p}\frac{dP}{P} = -\frac{g}{R}\int_0^h\frac{dh}{T_{SL}-Lh}$$
$$\frac{P}{P_{SL}} = \left(1-\frac{Lh}{T_{SL}}\right)^{-\frac{g}{RL}}$$





International Standard Atmosphere (ISA)

University of BRISTOL

International Standard Atmosphere (ISA)

$P_{SL} = 101.325\ kPa$

$T_{SL} = 288.15$ K

$\rho_{SL} = 1.225\ kg/m^3$

$g = 9.80665\ m/s^2$

$R = 287.1\ J/kg.K$

$Lapse\ Rate, L = 0.0065\ K/m$

$P = \rho RT$

$a = \sqrt{\gamma RT}$

Geopotential

Altitude, h		Temperature, T		Pressure, P	Density, ρ	Speed of Sound, a
m	ft	K	°C	kPa	kg/m³	m/s
0	0	288.15	15	101.3	1.225	340
1000	3281	281.65	8.5	89.9	1.112	336
2000	6562	275.15	2	79.5	1.007	333
3000	9843	268.65	-4.5	70.1	0.909	329
4000	13123	262.15	-11	61.6	0.819	325
5000	16404	255.65	-17.5	54.0	0.736	321
6000	19685	249.15	-24	47.2	0.660	316
7000	22966	242.65	-30.5	41.1	0.590	312
8000	26247	236.15	-37	35.6	0.525	308
9000	29528	229.65	-43.5	30.7	0.466	304
10000	32808	223.15	-50	26.4	0.413	299
11000	36089	216.65	-56.5	22.6	0.364	295
12000	39370	216.65	-56.5	19.3	0.311	295
13000	42651	216.65	-56.5	16.5	0.265	295
14000	45932	216.65	-56.5	14.1	0.227	295
15000	49213	216.65	-56.5	12.0	0.194	295
16000	52493	216.65	-56.5	10.3	0.165	295
17000	55774	216.65	-56.5	8.8	0.141	295
18000	59055	216.65	-56.5	7.5	0.121	295
19000	62336	216.65	-56.5	6.4	0.103	295
20000	65617	216.65	-56.5	5.5	0.088	295

Troposphere (0–11000 m):

$T = T_{SL} - (L \times h)$

$P = P_{SL} \times \left(1 - \left(\frac{L \times h}{T_{SL}}\right)\right)^{5.2561}$

Tropopause → 11000 m

Stratosphere (11000–20000 m):

$T = T_{11}$

$P = P_{11} \times e^{\left((-g\times(h-h_{11}))/(R\times T_{11})\right)}$

Key take-aways of Lecture 1

- Outline of contents of Unit
- Details of the types of Propulsion Systems currently used in aviation
- A brief description of the Joule or Brayton Cycle and its relevance to gas turbines.
- Description of the international Standard Atmosphere (ISA)

What's in Lecture 2?

- Recap on thermodynamics and basic relationships

- Explain and show the ideal efficiency of the Brayton cycle

- Show and calculate the main characteristics of a practical turbojet