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# Jet and Rocket Propulsion

## AE4451

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### LECTURE 15

what we saw last time:

- turbojets and turbojet cycle analysis

today:

- turbofans

## Overview

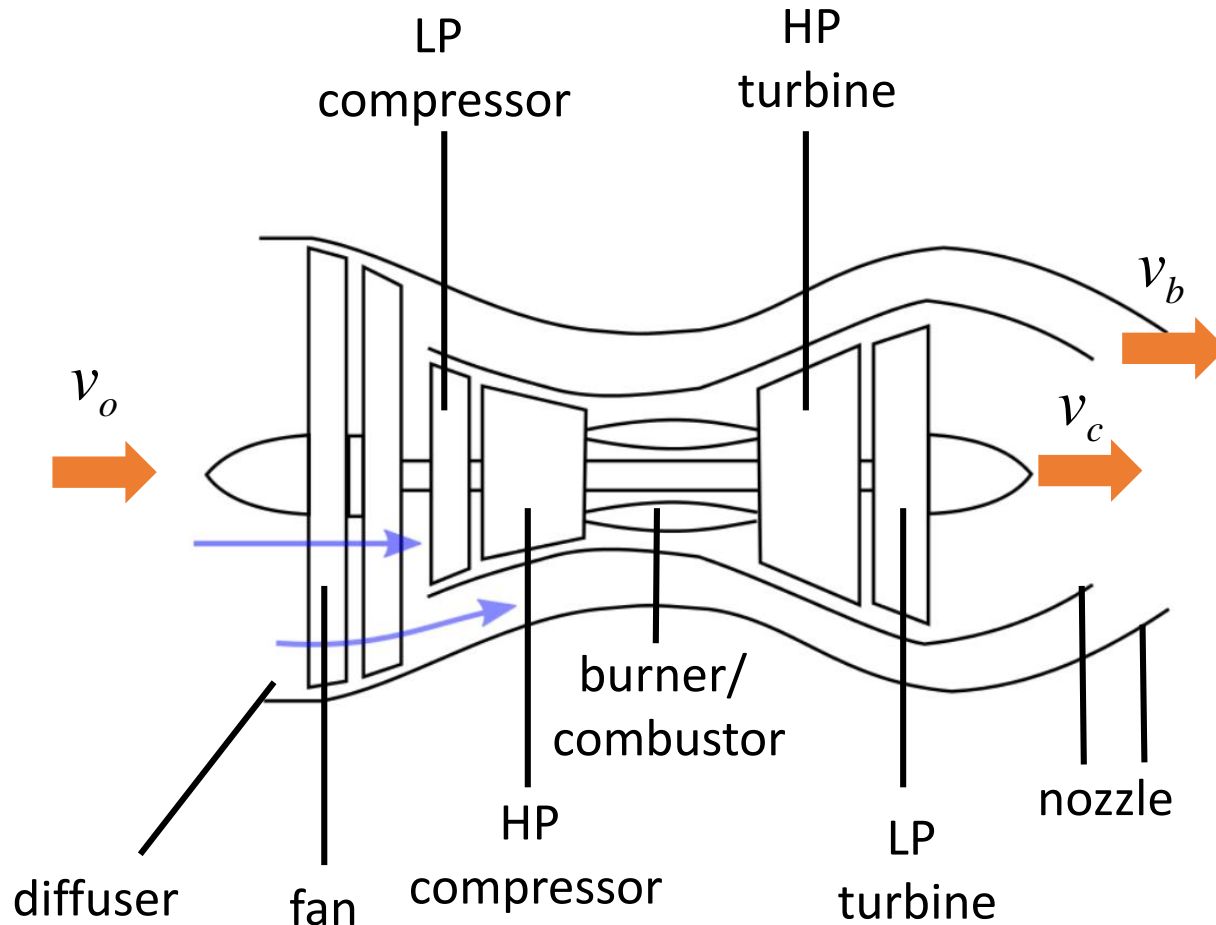
- first turbofan engine: Daimler Benz DB 007 (Karl Leist) in 1943
- idea: increase propulsive efficiency
  - use more air with lower exit velocity to increase thrust
  - more economical than turbojet in subsonic flight
  - improve range/reduce fuel consumption
- several configurations
  - forward or aft fans
  - unmixed or mixed nozzles



Pratt and Whitney JT9D  
first turbofan to power large airliner (1965)

# Turbofans

## Structure and operation



- thrust increase achieved with bypass air flow (ignoring pressure contribution)

$$F_T = F_c + F_b \quad \text{total thrust}$$

$$F_c = (\dot{m}_c + \dot{m}_f)v_c - \dot{m}_c v_o \quad \text{core thrust}$$

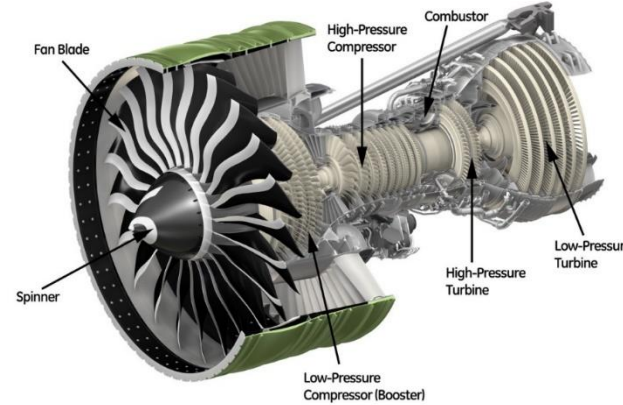
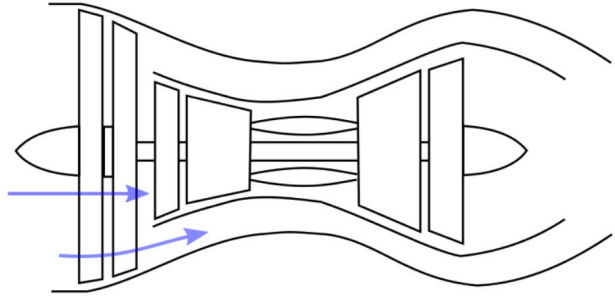
$$F_b = \dot{m}_b(v_b - v_o) \quad \text{bypass thrust}$$

$$\text{bypass ratio (BPR)} \quad \beta = \frac{\dot{m}_b}{\dot{m}_c}$$

- fan on LP (low pressure) spool which spins at lower speed than outer concentric HP (high pressure) spool
- separation into spools: to compensate for higher tip speed of larger diameter components by rotating slower

## Structure and operation

### Forward fans



GE90-115B

### advantages

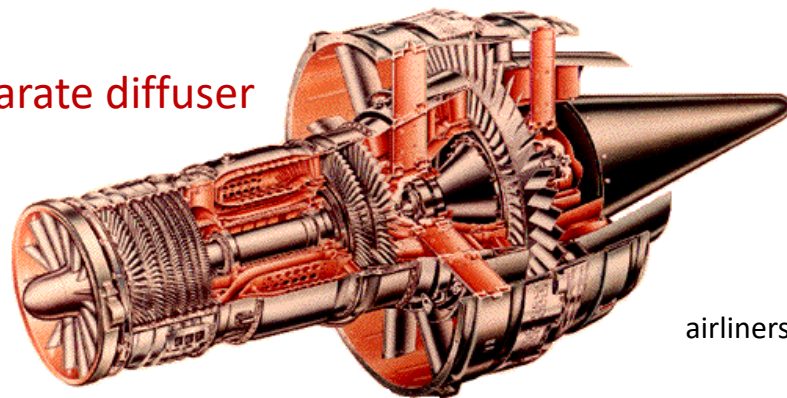
- high fuel efficiency (increased air volume) and thrust
- fan covered by cowling/duct (protected, aerodynamic control possible)

### disadvantages

- large frontal area, complexity

### Aft fans

separate diffuser



airliners.net

GE CF700

### advantage

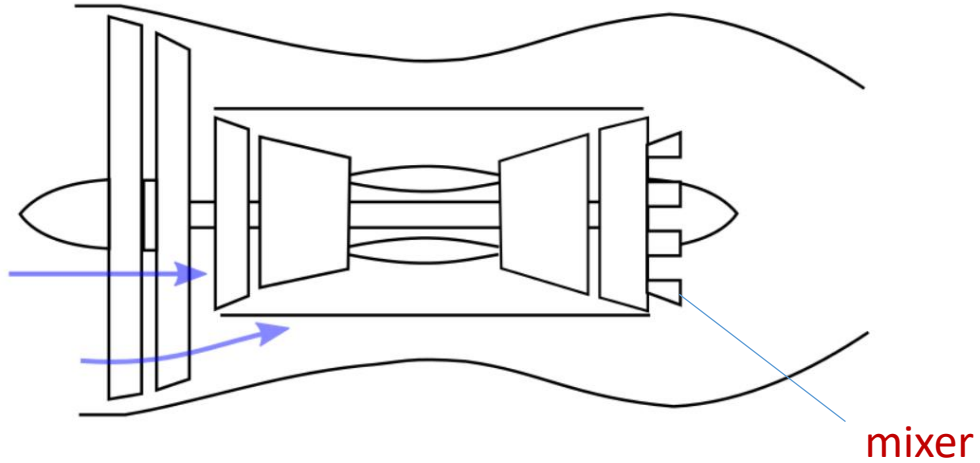
- simpler architecture than forward fan

### disadvantages

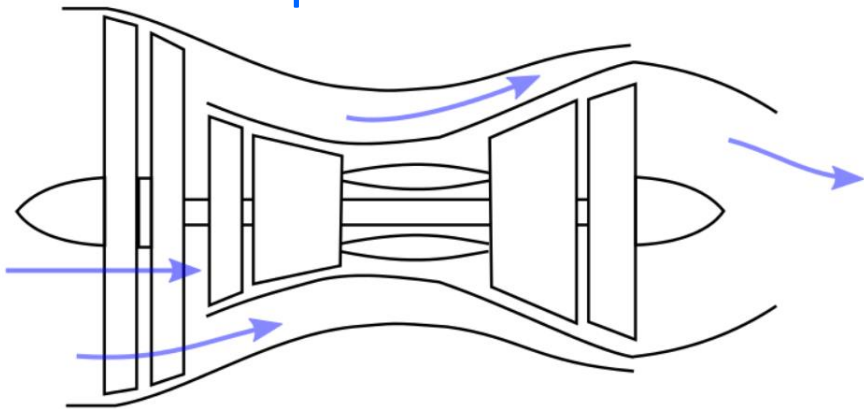
- no contribution to air compression at inlet

## Structure and operation

### Single/mixed nozzle



### Separate nozzles



### advantages

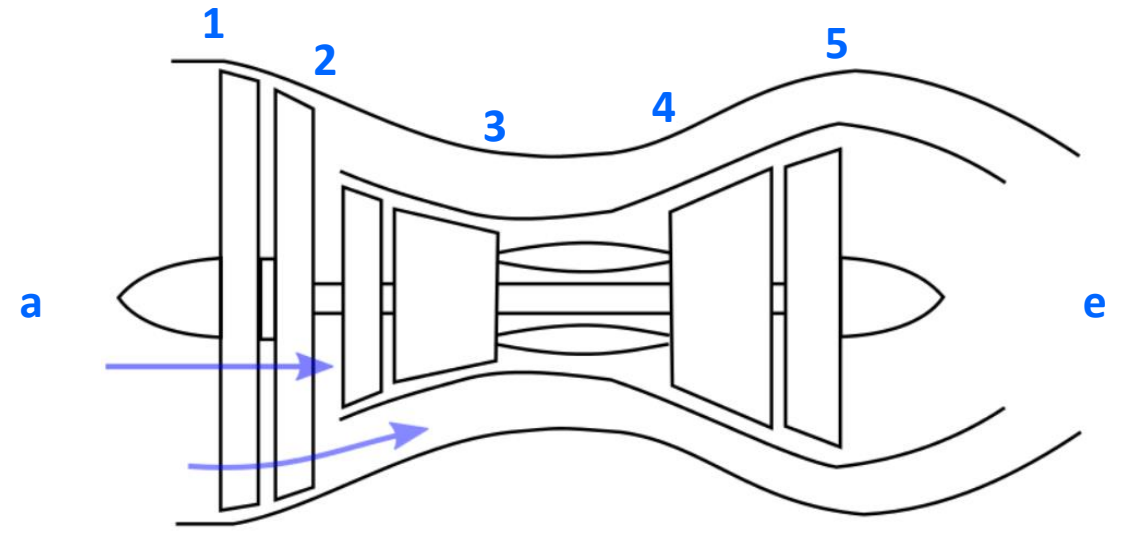
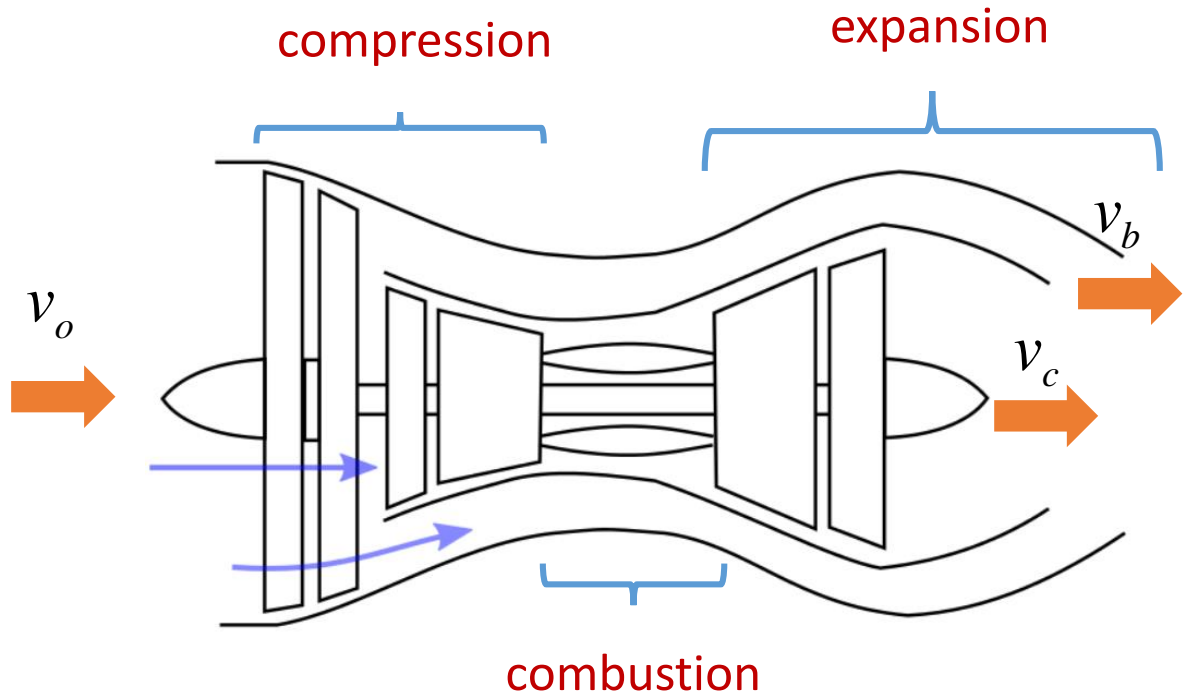
- can reduce noise (reduction of exit velocity of core air)
- can reduce exhaust heat (e.g. military aircraft)
- some increase in thrust, lower TSFC

### advantage

- structural simplicity

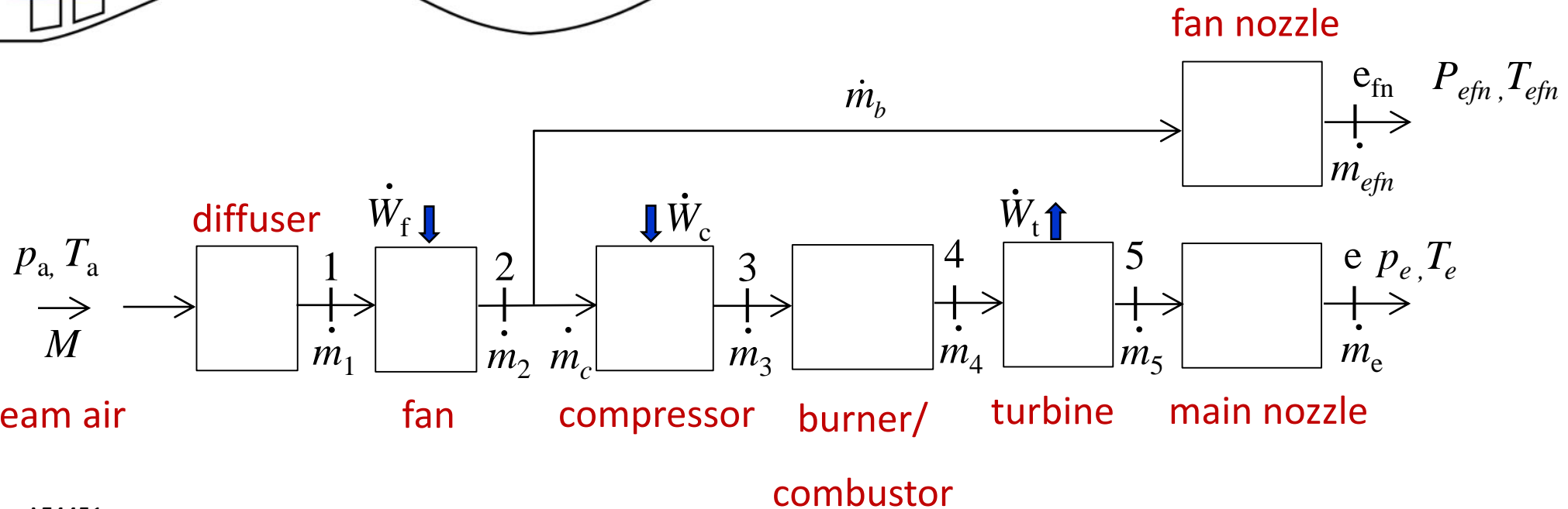
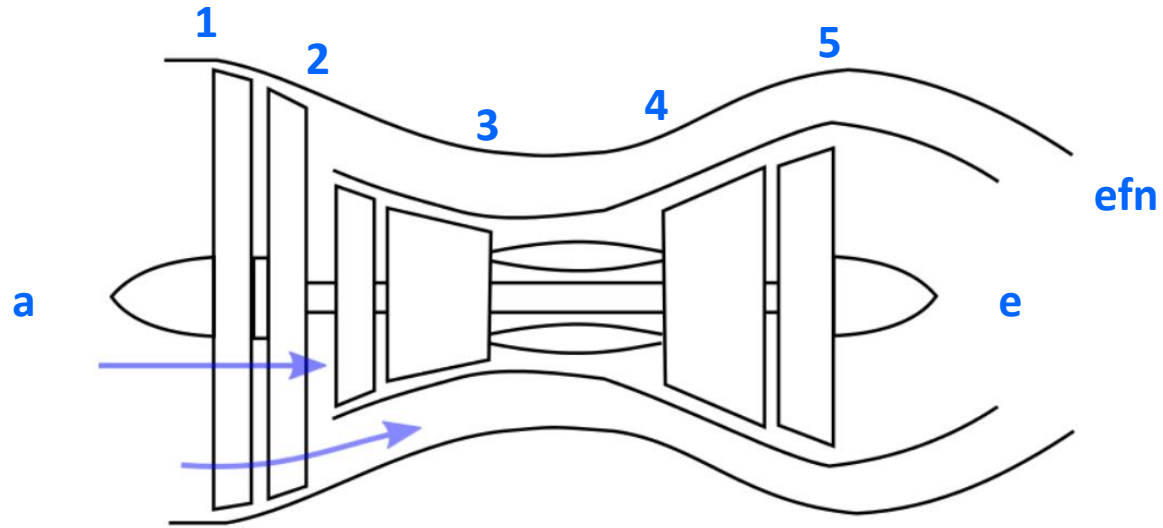
# Turbofans

## Structure and operation



# Turbofans

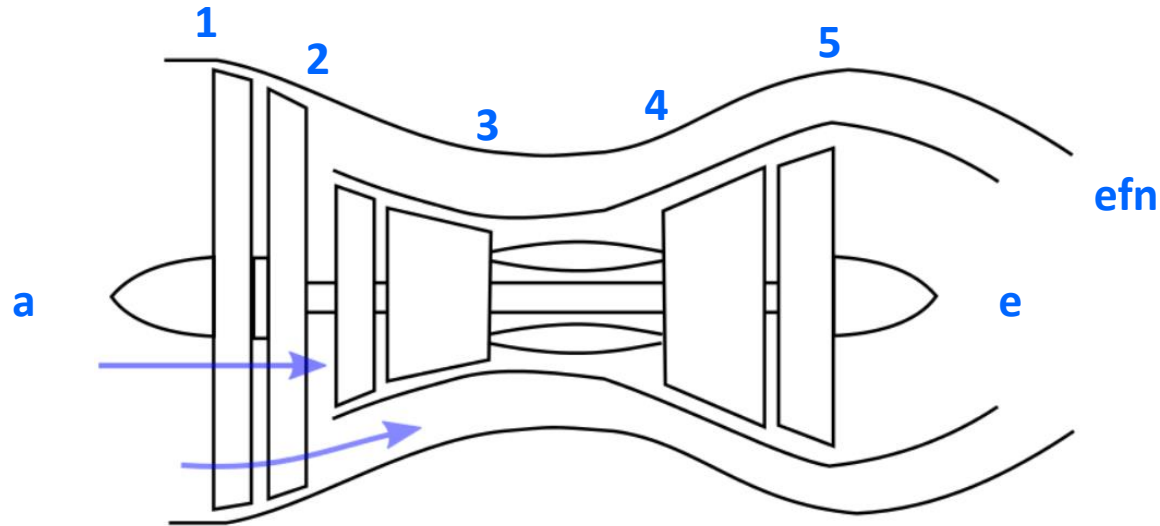
## Structure and operation



## Ideal cycle analysis

- assume fully expanded nozzle, where  $p_e = p_a$
- isentropic, reversible expansion and compression
- assume for simplicity the same  $c_p$  throughout each component

## Ideal cycle analysis: diffuser (common to core and bypass)



Mass

$$\dot{m}_a = \dot{m}_1$$

Energy

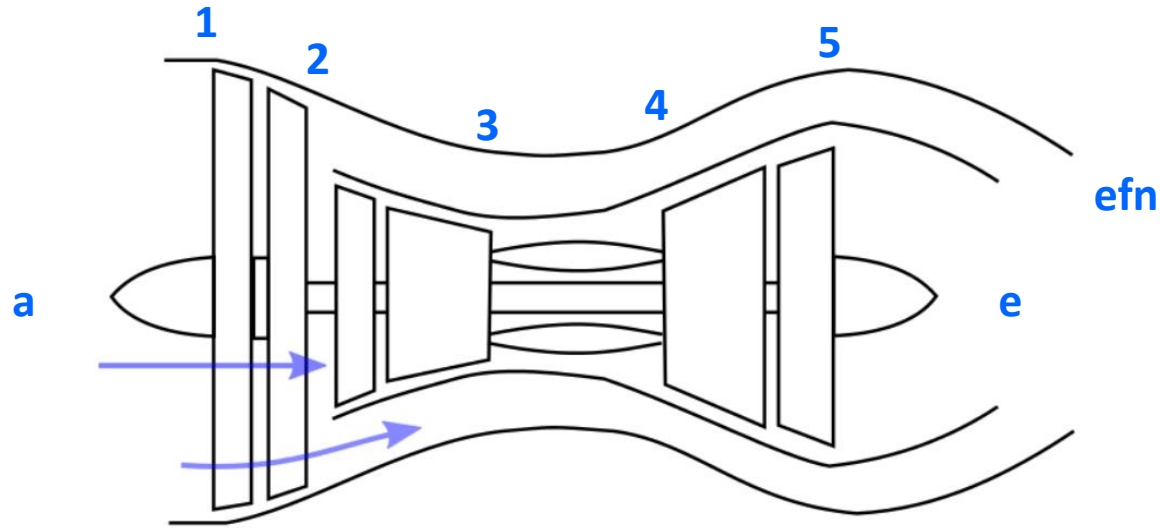
$$\dot{m}_a h_{oa} = \dot{m}_a h_{o1}$$

$$\Rightarrow T_{oa} = T_{o1}$$

$$\Rightarrow T_{o1} = T_a \left( 1 + \frac{\gamma - 1}{2} M^2 \right)$$

# Turbofans

Ideal cycle analysis: fan (common to core and bypass)



Mass

$$\dot{m}_1 = \dot{m}_2$$

Energy

$$\dot{W}_t = \dot{W}_f + \dot{W}_c$$

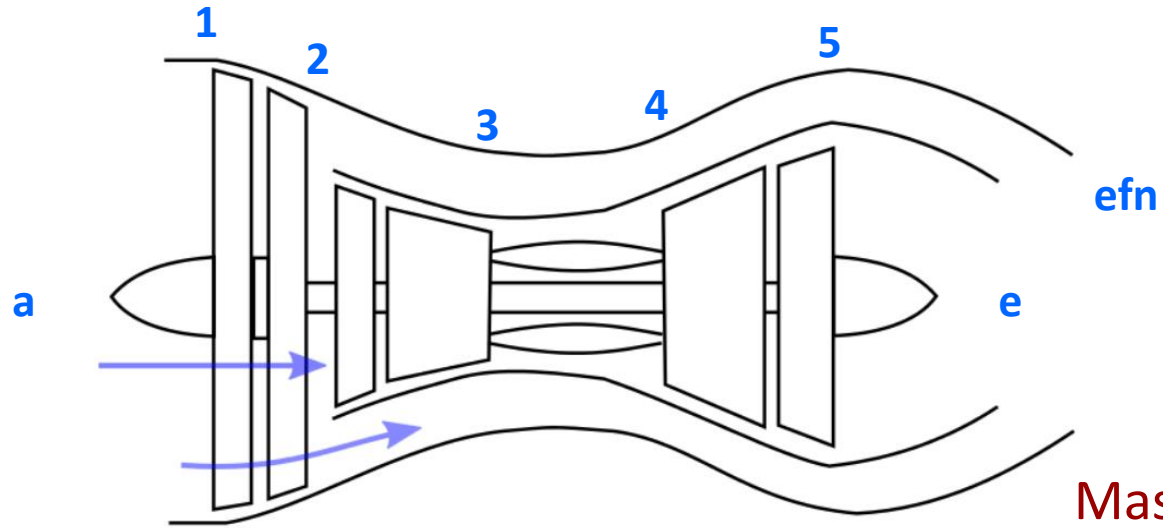
$$T_{o2} = T_{o1} \left( \frac{P_{o2}}{P_{o1}} \right)^{\frac{\gamma-1}{\gamma}}$$

$$\dot{W}_f = \dot{m}_2 c_p (T_{o2} - T_{o1}) \quad \text{work on fan}$$

fan pressure ratio  
(FPR) or  $Pr_f$   $\frac{P_{o2}}{P_{o1}}$

# Turbofans

## Ideal cycle analysis: fan (bypass-only section)



Mass

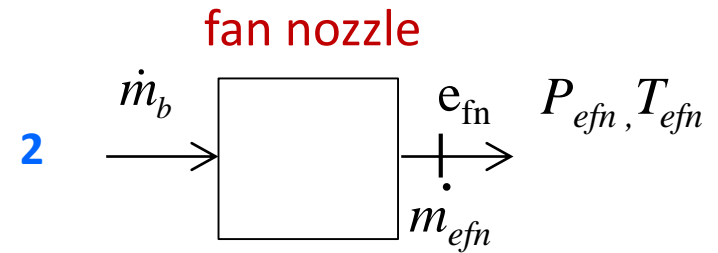
Energy

assume mass flow rate out of fan = sum of mass flows into core and bypass

$$\dot{m}_2 = \dot{m}_c + \dot{m}_b$$

$$\dot{m}_2 = \dot{m}_c (1 + \beta)$$

specified



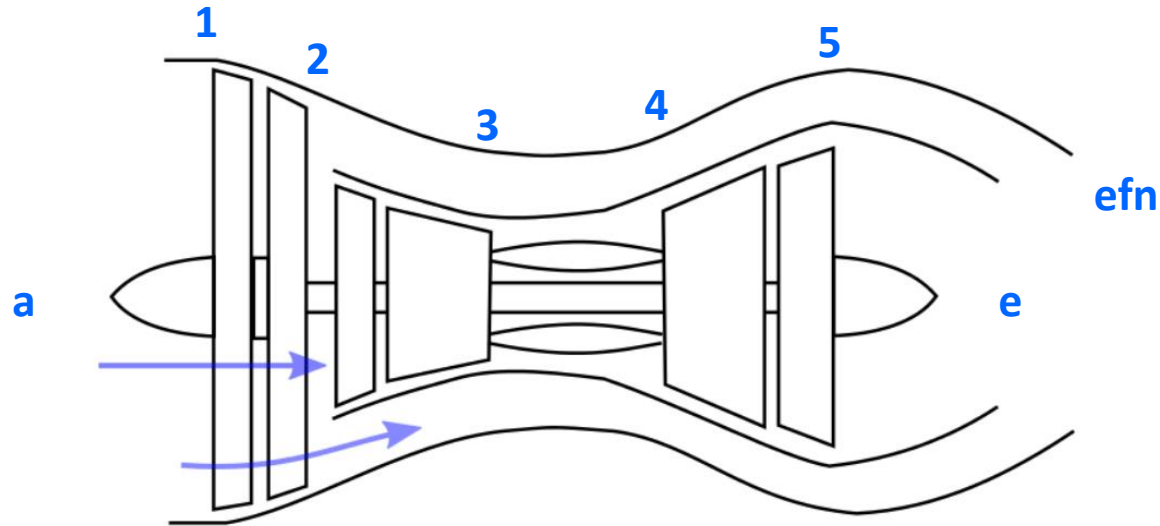
$$\dot{m}_b = \dot{m}_{efn}$$

$$\dot{m}_b h_{o2} = \dot{m}_{efn} h_{oefn}$$

$$T_{o2} = T_{oefn}$$

$$T_{oefn} = T_{o1} \left( \frac{P_{o2}}{P_{o1}} \right)^{\frac{\gamma-1}{\gamma}}$$

## Ideal cycle analysis: core (compressor)



Mass  $\dot{m}_3 = \dot{m}_c$

Energy  $T_{o3} = T_{o2} \left( \frac{p_{o3}}{p_{o2}} \right)^{\frac{\gamma-1}{\gamma}}$

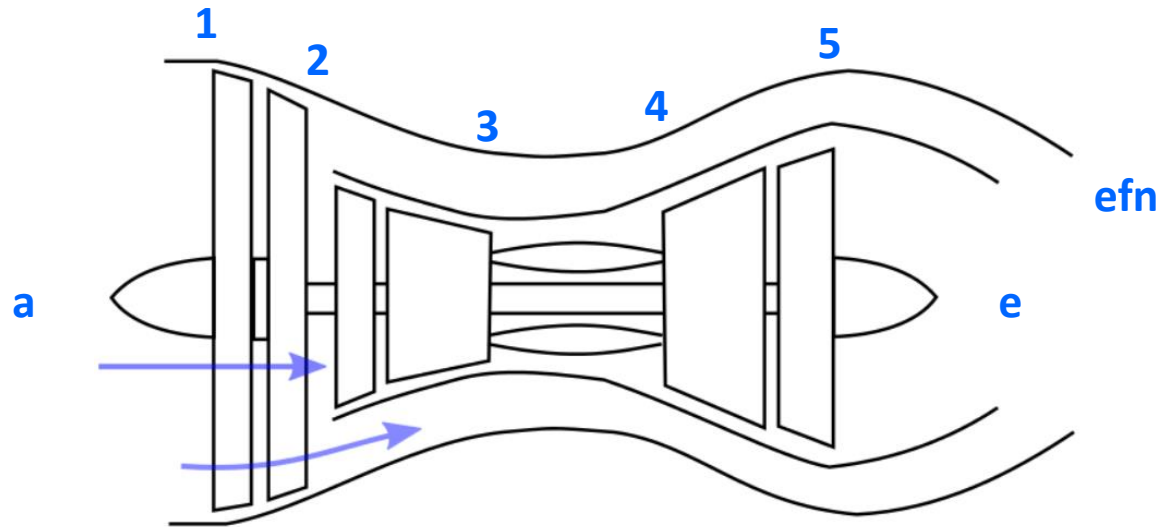
$\dot{W}_c = \dot{m}_3 c_p (T_{o3} - T_{o2})$

work on  
compressor

compressor pressure ratio  $Pr_c = \frac{p_{o3}}{p_{o2}}$

# Turbofans

## Ideal cycle analysis: core (burner)

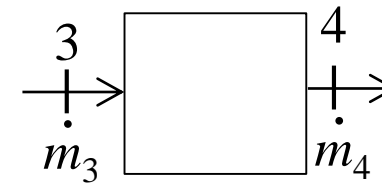


Mass

$$\dot{m}_c + \dot{m}_f = \dot{m}_3 + \dot{m}_f = \dot{m}_4$$

$$\dot{m}_4 = \dot{m}_c (1 + f)$$

Energy



burner/

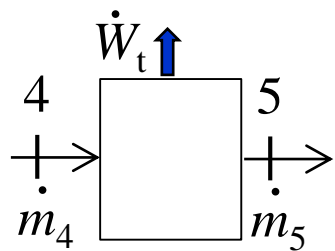
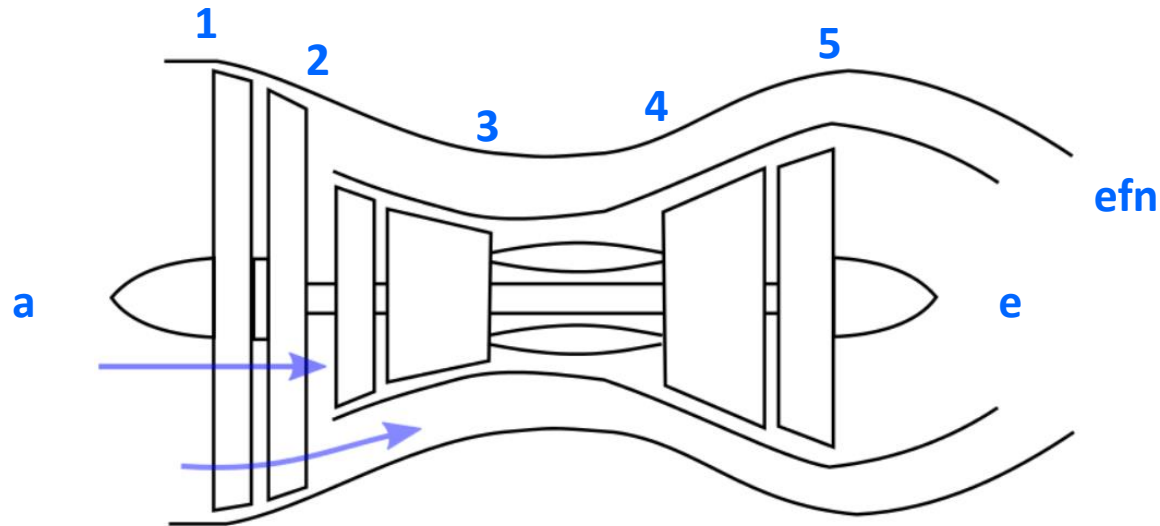
combustor

$$f = \frac{T_{o4}/T_{o3} - 1}{\left(\frac{\Delta h_R}{c_p T_{o3}}\right) - T_{o4}/T_{o3}}$$

$$\frac{P_{o4}}{P_{o3}} = P_{rb} \quad \text{burner pressure ratio}$$

# Turbofans

## Ideal cycle analysis: core (turbine)



turbine

Mass

$$\dot{m}_5 = \dot{m}_4 \quad \dot{W}_t = \dot{W}_f + \dot{W}_c$$

Energy

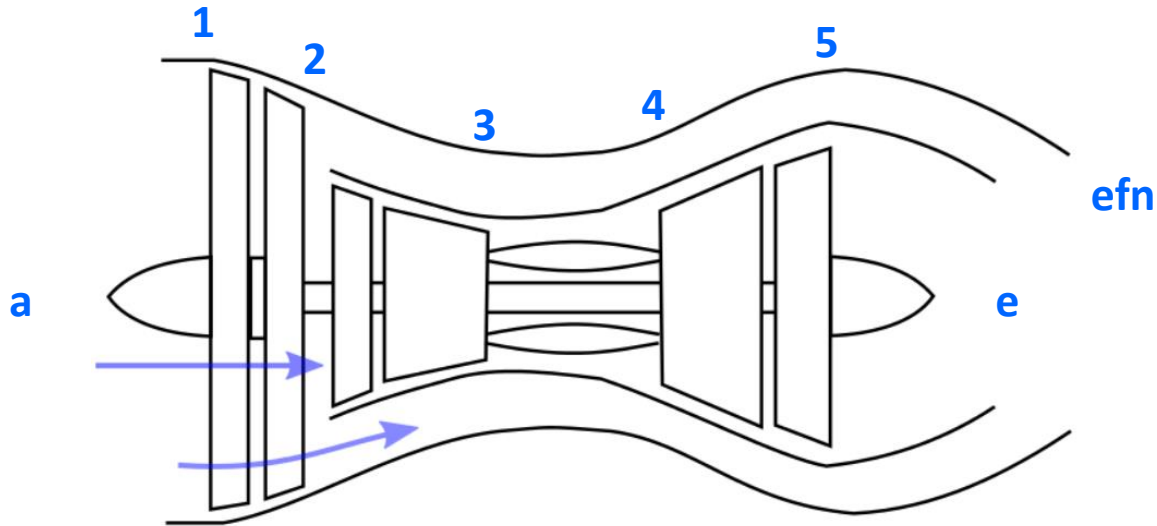
$$T_{o5} = T_{o4} - \frac{\dot{W}_t / \dot{m}_a}{c_p (1 + f)}$$

$$p_{o5} = p_{o4} \left\{ 1 - \frac{1}{\eta_t} \left( 1 - \frac{T_{o5}}{T_{o4}} \right) \right\}^{\frac{\gamma}{\gamma-1}}$$

if accounting for a turbine efficiency, just as with turbojet

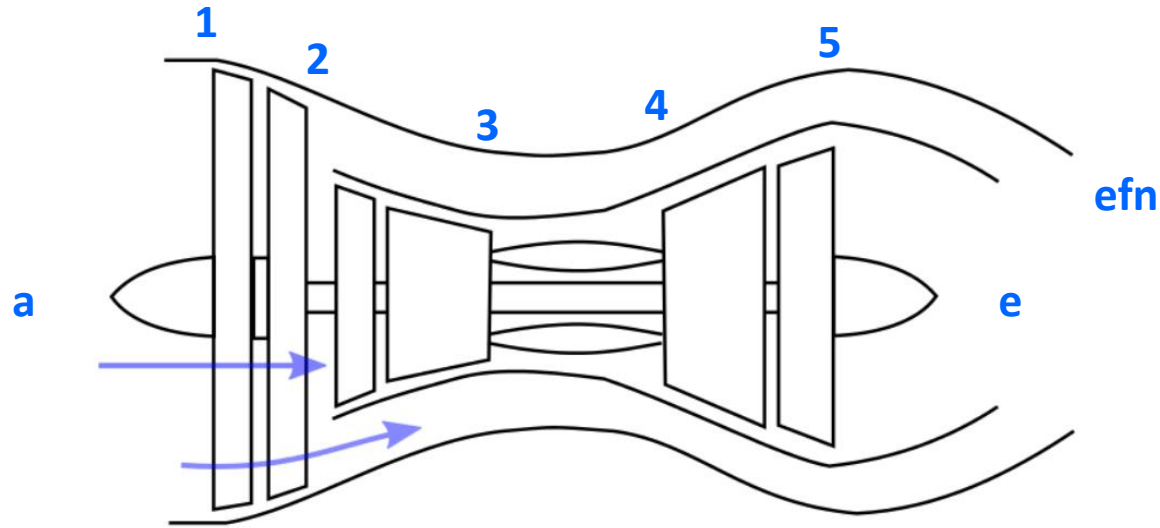
here, simply 
$$p_{o5} = p_{o4} \left( \frac{T_{o5}}{T_{o4}} \right)^{\frac{\gamma}{\gamma-1}}$$

## Ideal cycle analysis: core (afterburner)



- note that some mixed flow-architectures are fitted with afterburners
- this would be on the core section
- check out turbojet analysis for how we dealt with the presence of an afterburner
  - two sources of fuel injection
  - add another component to analysis

## Ideal cycle analysis: core (nozzle)



$$\dot{m}_e = \dot{m}_5$$

$$T_e = T_{o5} \left( \frac{p_e}{p_{o5}} \right)^{\frac{\gamma_n - 1}{\gamma_n}} \quad \text{ignoring nozzle efficiency}$$

$$u_e = \sqrt{2c_p (T_{o5} - T_e)}$$

## Performance

Consider a non-ideal turbofan configuration

- forward fan with separate nozzles
- bypass ratio  $\beta = 5$
- fan pressure ratio  $Pr_f = 1.5$

sample component efficiencies:

Component	Efficiency
Diffuser	90%
Fan/Compressors*	90%
Combustor	99%
Turbines*	91%
Nozzles	95%

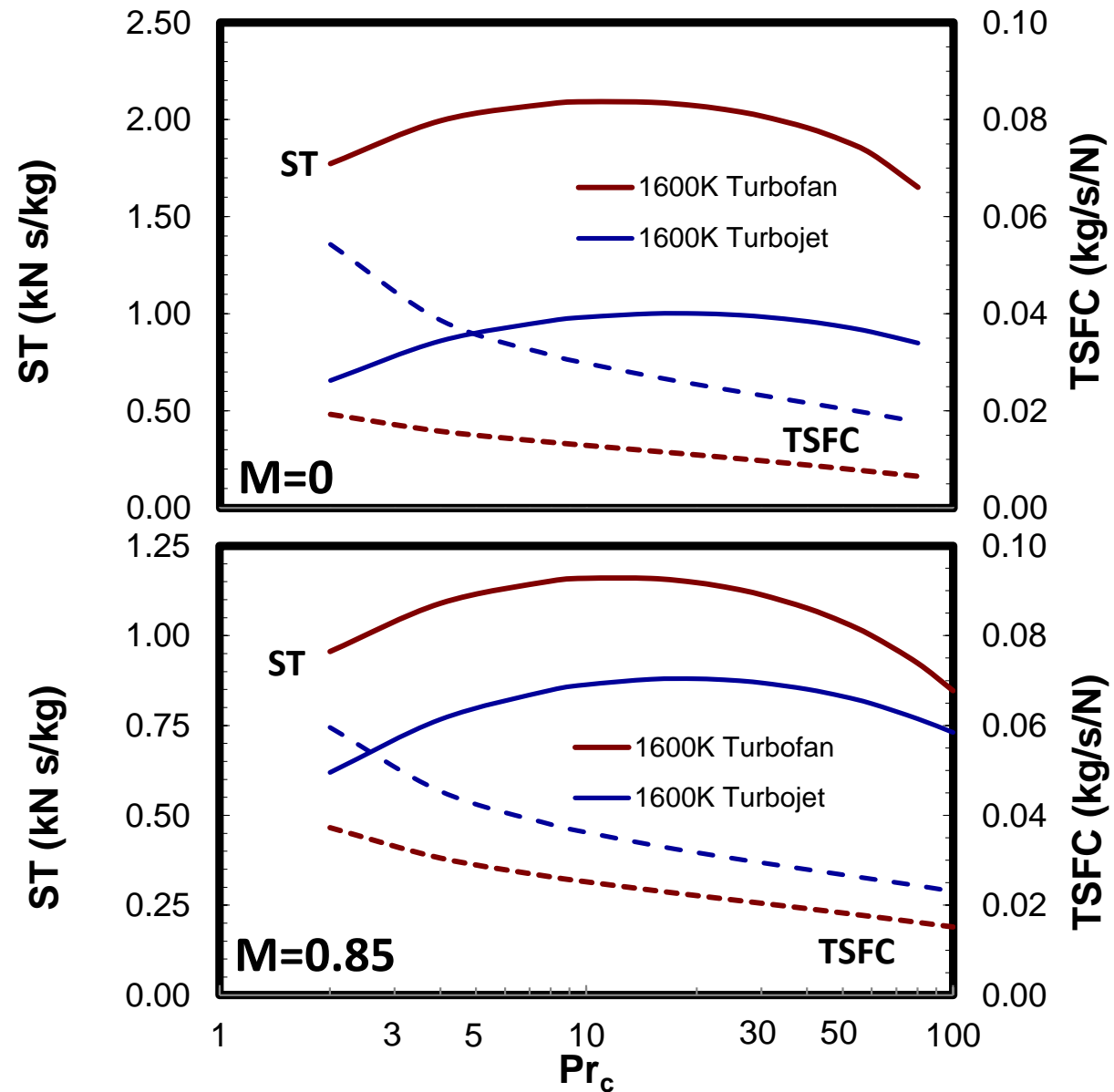
\* *polytropic efficiency*

Polytropic efficiency convenient for multistage devices, rather than ideal isentropic adiabatic efficiency

# Turbofans

## Performance: turbofan vs turbojet

- why is turbofan specific fuel consumption lower?
- why is the specific thrust higher?
- why does the improvement decrease at higher M?
  - high BPR turbofan ( $\beta > 5$ ): 75% thrust from bypass
  - low bypass ( $\beta \sim 1$ ): 50%

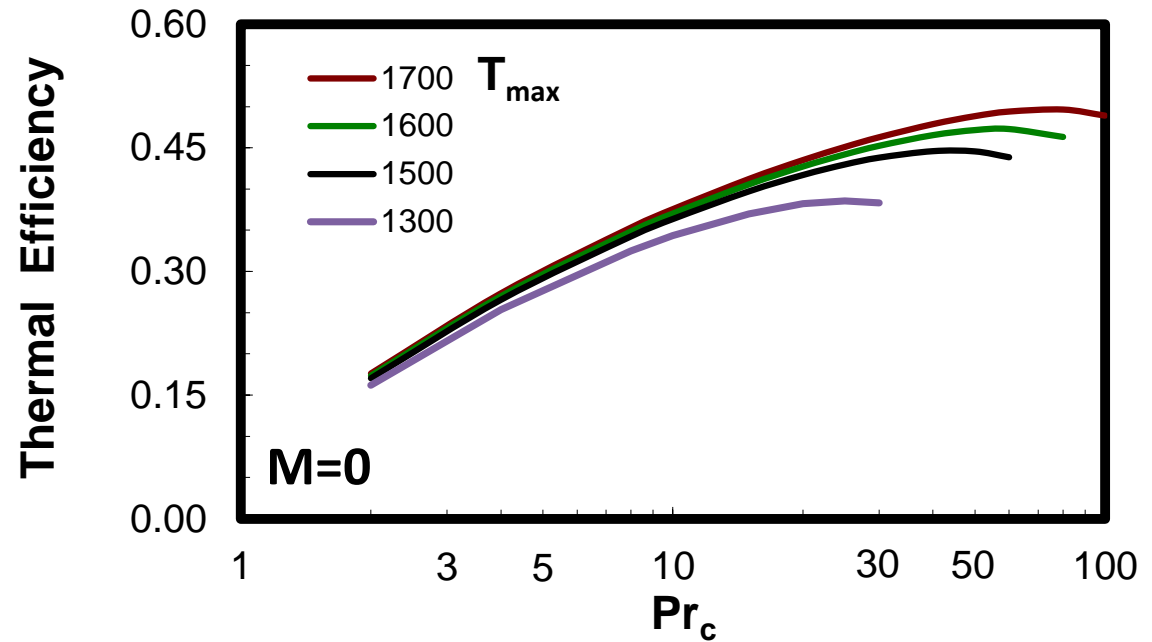


# Turbofans

## Performance: thermal efficiency

- slight change to thermal efficiency with increasing  $T_{max}$
- dominant effect is compressor pressure ratio

$$\eta_{th} = \frac{(1+f)u_e^2 - u^2}{2f\Delta h_R}$$



## Performance: propulsive efficiency

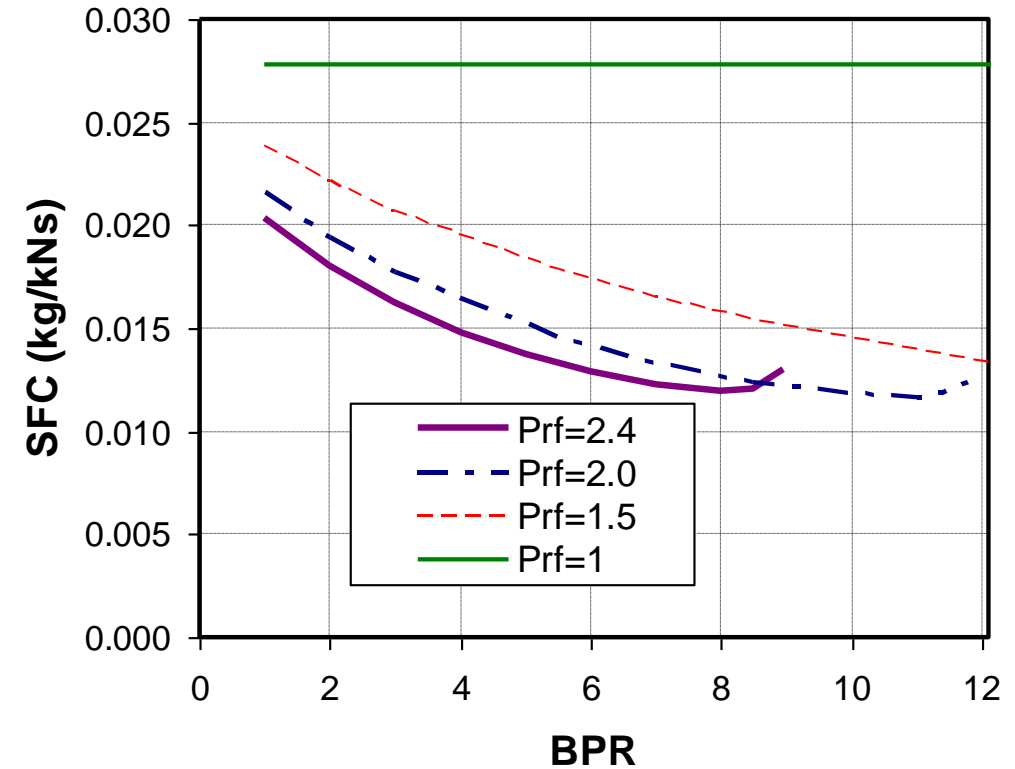
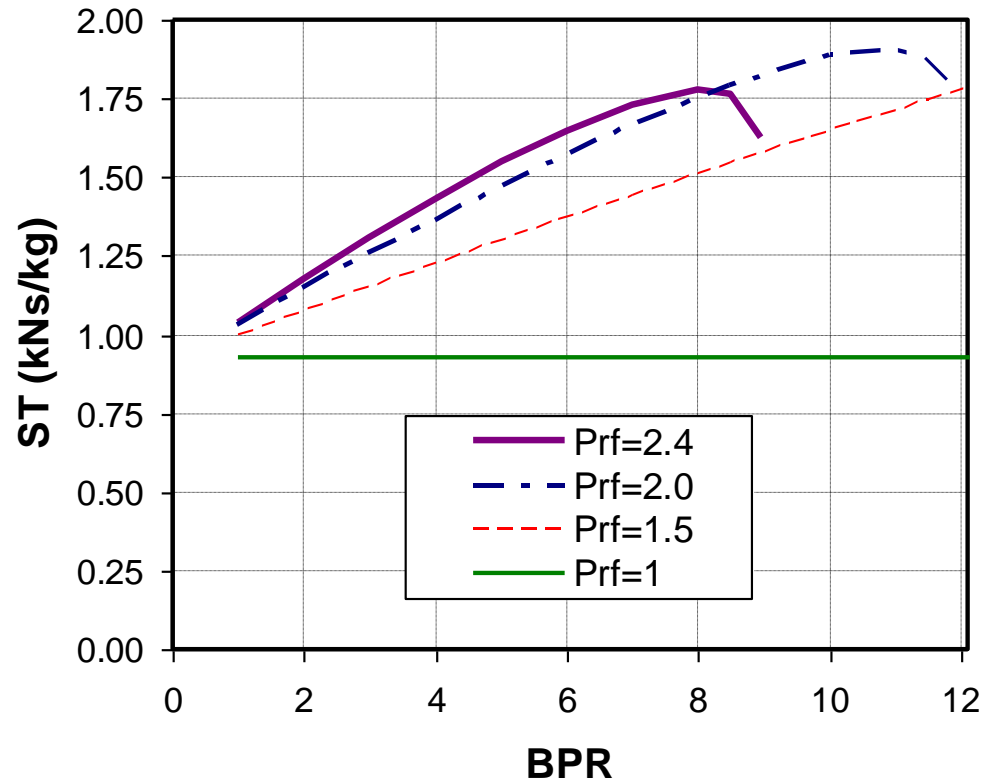
$$\eta_p = \frac{2}{(u_e/u + 1)}$$

$$\eta_p = \frac{\tau u}{\Delta KE}$$

- from ratio of propulsive power to change in kinetic energy of moving air stream

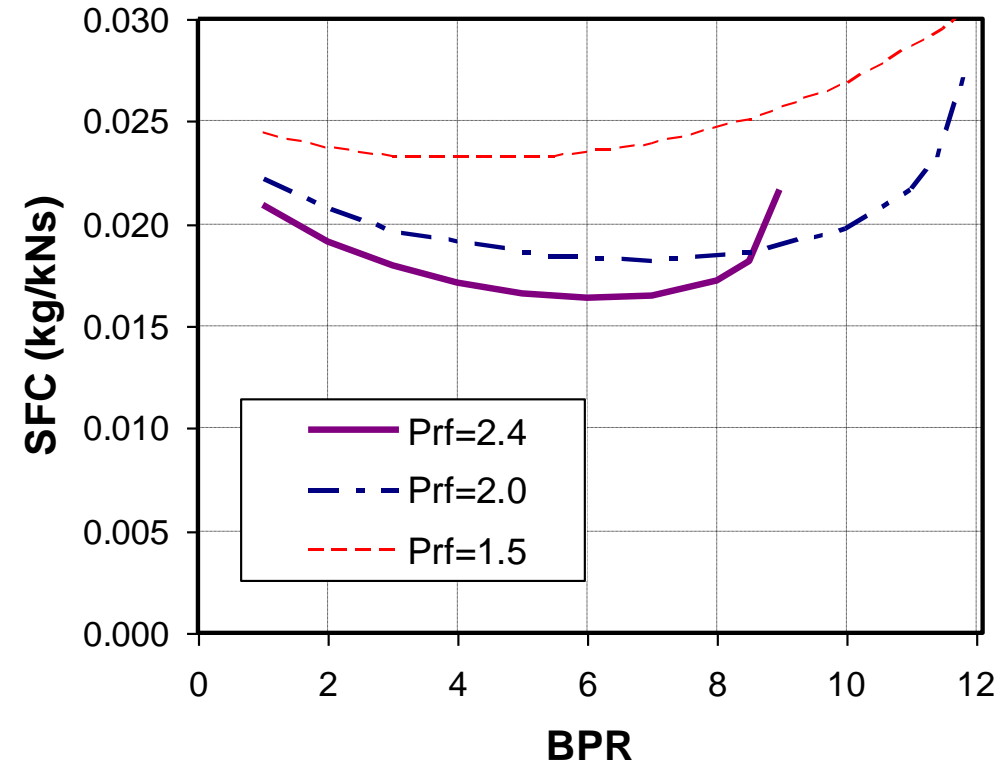
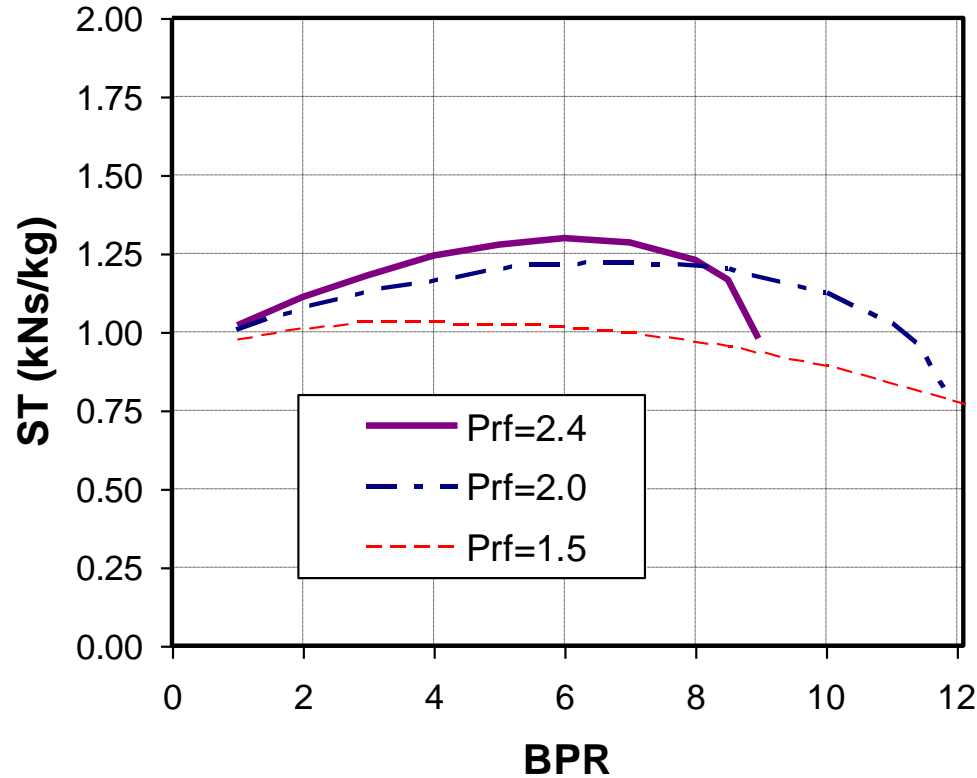
- ideally, want to move maximum amount of air with minimum change in kinetic energy

## Performance: optimum BPR (bypass ratio) and $Pr_f$ (fan pressure ratio)



- optimum bypass ratio depends on fan pressure ratio (also on  $M$ ,  $T_4$ ,  $P_{rc}$  – compressor ratio)
- thrust starts to drop at high BPR (and SFC increases) – why?
- real optimum also depends on component efficiencies

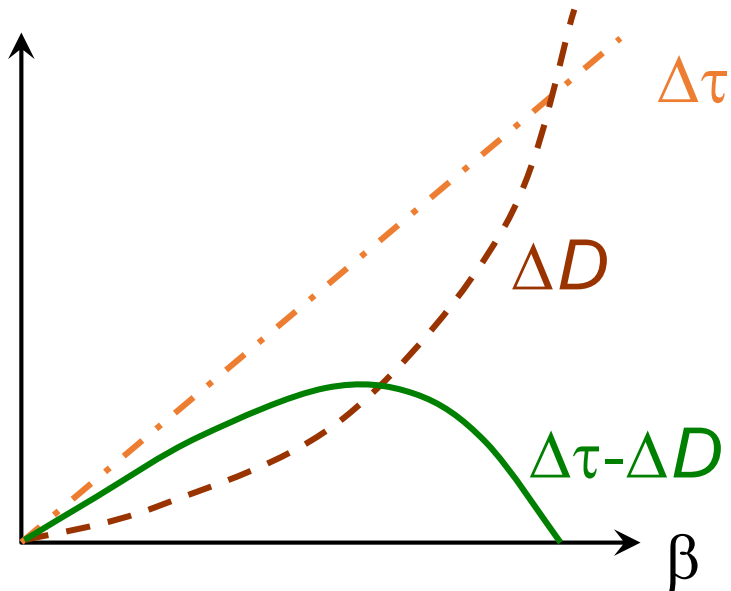
## Performance: drag effect on optimum bypass



$T_4=1500K$   
 $Pr_c=20$   
 $M=0.85$

- above figures for ideal case but now accounting for drag due to larger inlet
- shift of optimum bypass ratio to lower values

## Performance: added thrust



- added thrust ( $\Delta\tau$ ) developed with bypass scales roughly linearly with bypass ratio  $\beta$
- drag induced in flight (for given  $u$ , altitude, ...) increases with inlet size and larger inlet needed as  $\beta$  increases  
(if core size not reduced)
- increased drag ( $\Delta D$ )  $\propto \beta^n$  with  $n > 1$

The effective thrust increment is the difference,  $\Delta\tau - \Delta D$

## Performance: takeoff vs cruise bypass

### Takeoff

- usually maximum power requirement (commercial/civilian aircraft): large thrust required
- relatively low aircraft velocity and low drag conditions  $D \propto u^2$ 
  - large effective thrust

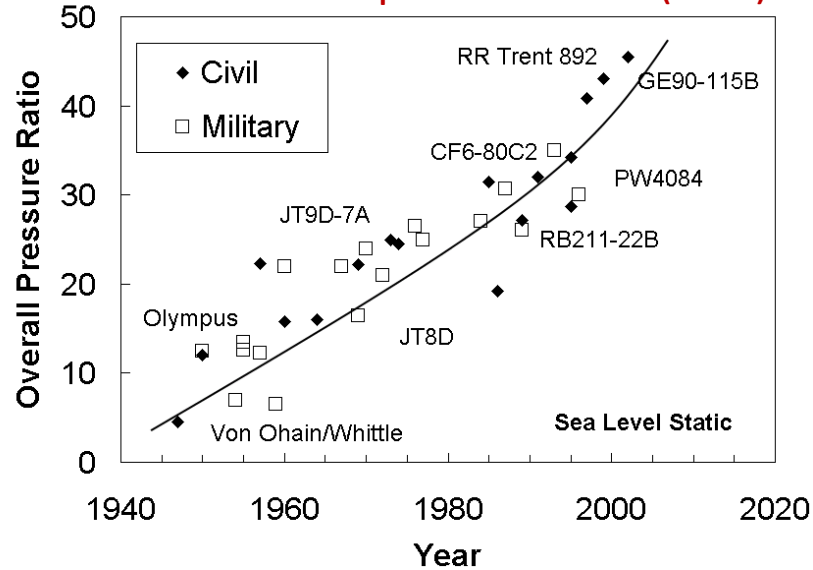
### Cruise

- low thrust required (lower  $\beta$  needed) and higher drag conditions
  - higher effective thrust penalty

The optimum bypass: tradeoff

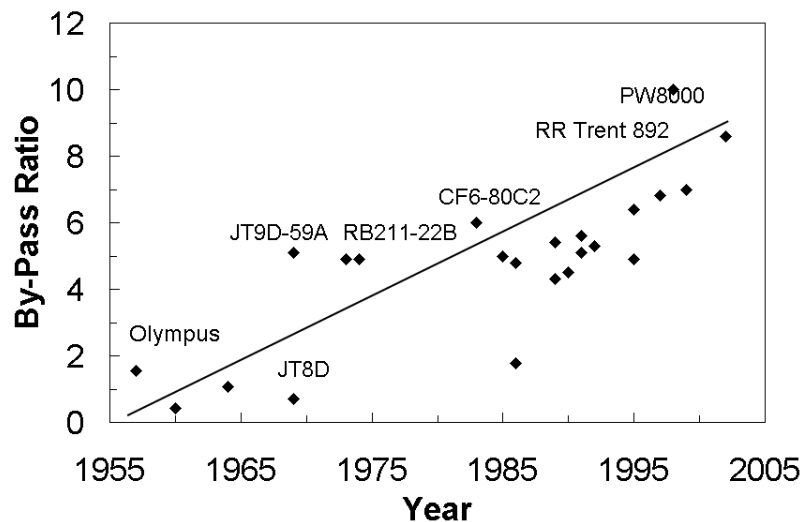
## Trends

overall pressure ratio (OPR)



- overall pressure ratio (OPR) increases with number of stages
- GE9x: close to 60

bypass ratio (BPR)

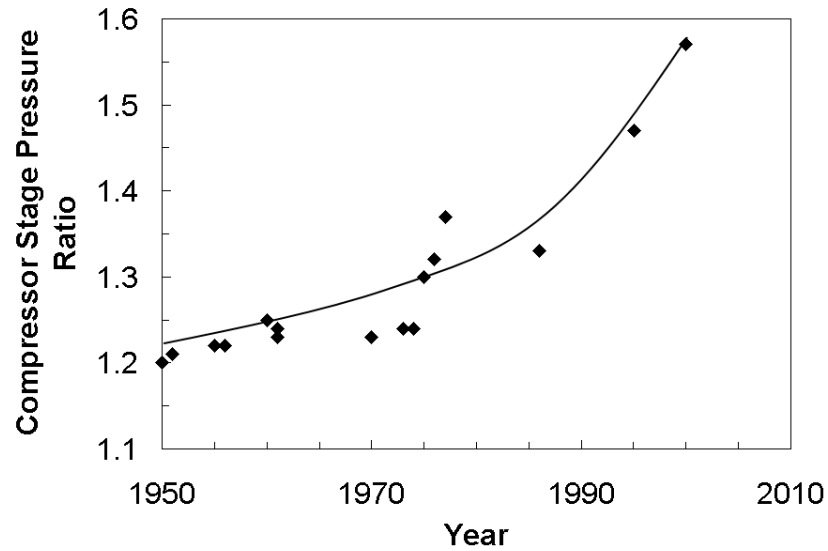


- current technology: max BPR 12-13

*from Ballal and Zelina*

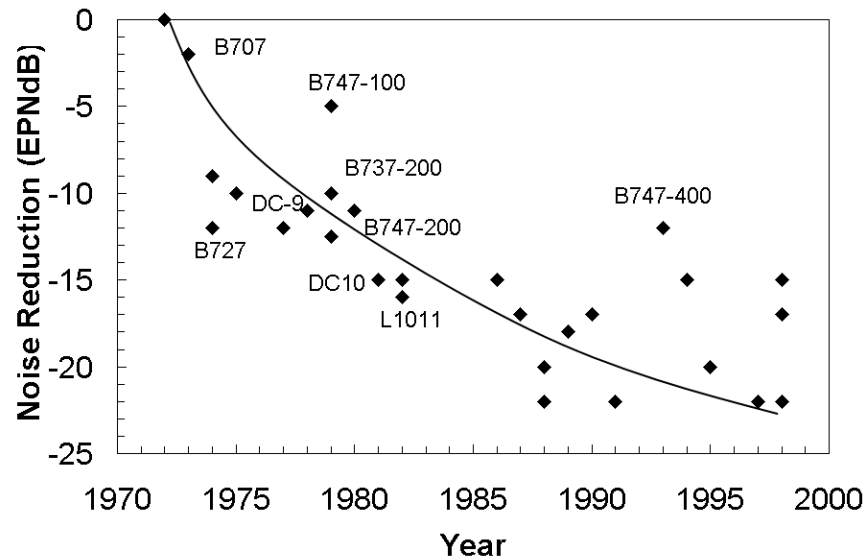
## Trends

compressor stage pressure ratio (OPR)



- increase due to improved blade design: materials and aerodynamics

effective perceived noise in dB (EPNdB)



- decrease seen with turbofans and increased BPRs

*from Ballal and Zelina*