

Lecture 4 - Propulsion

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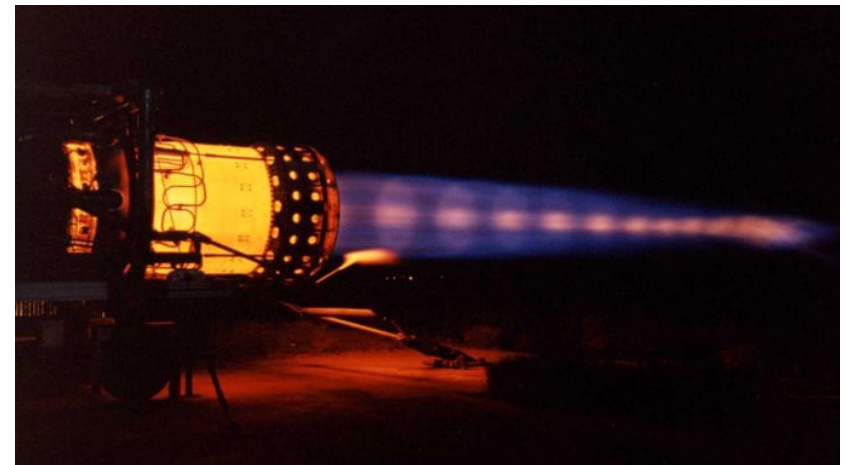
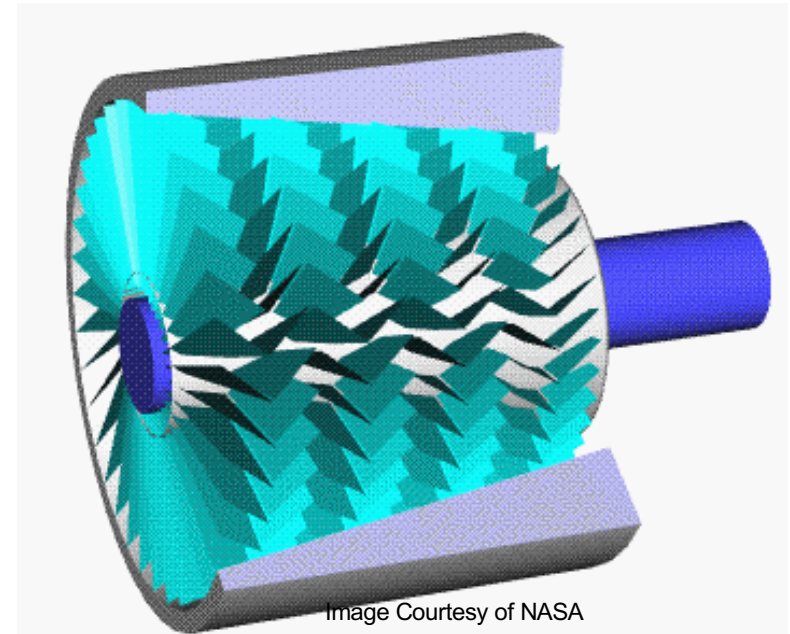


Image Courtesy of USAF

Aircraft Propulsion Systems

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- **4 main categories**
 - **Piston Engines**
 - Otto and diesel cycle engines
 - Normally drive propellers
 - **Jet engines**
 - Turbojets
 - Turbofans
 - Turboprops
 - Pulse jets
 - Ram jets
 - **Rocket engines**
 - Very high specific fuel consumption
 - Only practical for hypersonic applications
 - **Electric motors**
 - Very Quiet
 - Energy storage limitations, but getting better



Piston Engines Overview

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- **T: Thrust**
- **V: Velocity**
- **P_{AV} : Power Available**
- **BHP: brake-horse-power, also called shaft-horse-power, SHP**
- **η_p : Propeller efficiency**



$$P_{AV} = \eta_p (BHP) = TV$$
$$\eta_p = \frac{TV}{BHP} = \frac{P_{AV}}{P_{SHP}}$$

Piston Engines Overview

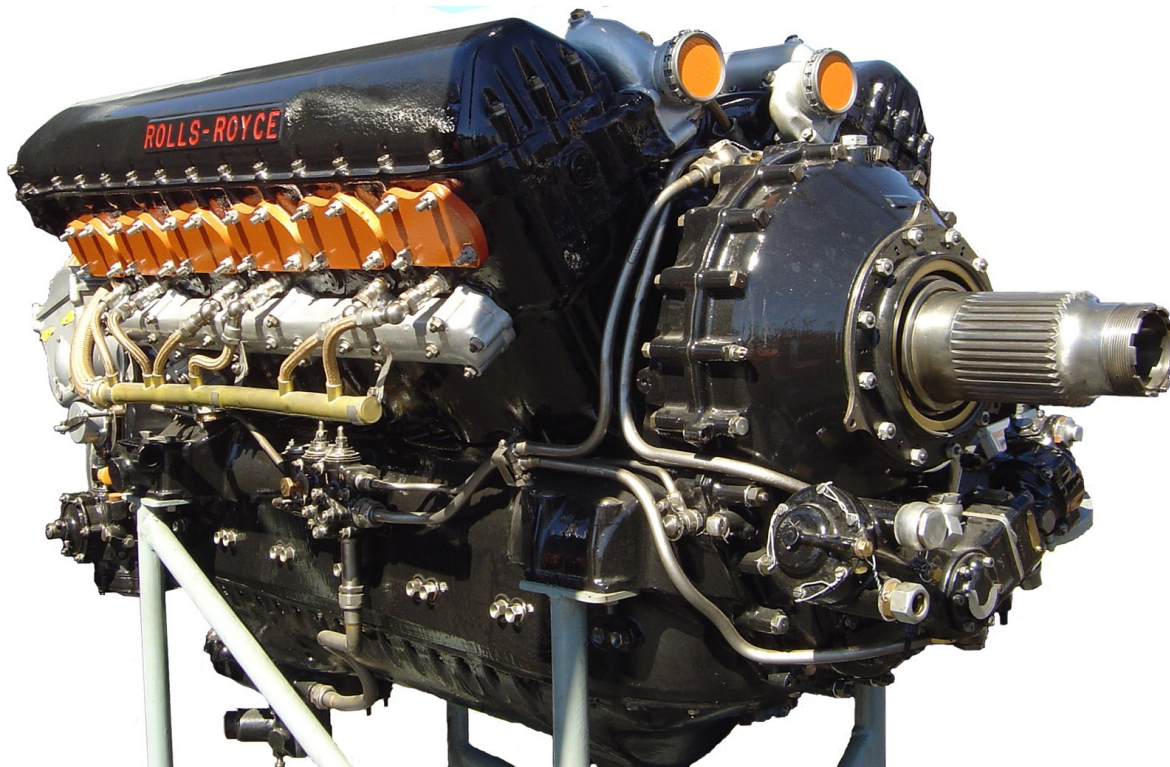
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- A piston engine produces work by turning a propeller. It does not generate thrust directly
- Power generated by engine is converted into propulsive power by the propeller
- Propellers will never be able to convert all engine power into propulsive power. The propeller efficiency is the ratio of propulsive power (power available to the aircraft) to the engine power
- In this class we sometimes assume constant propeller efficiency. When this is true, how do P_{AV} and thrust vary with velocity for a constant engine power?



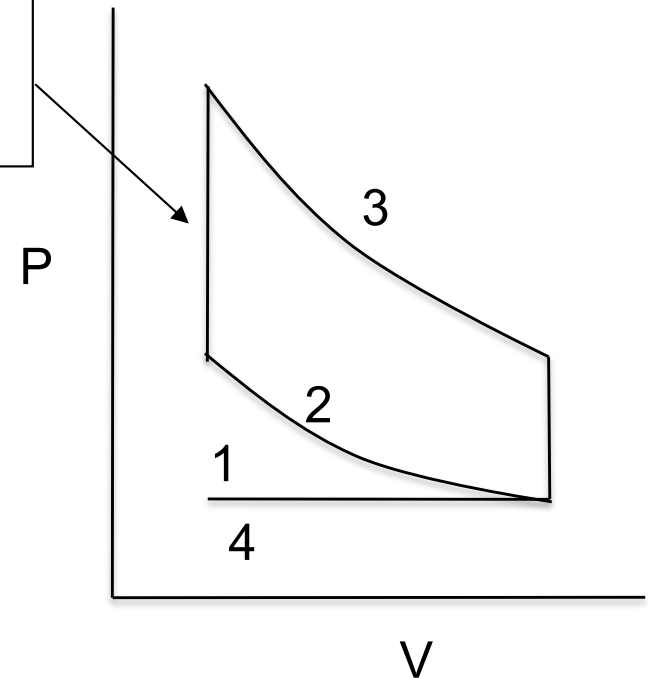
Four Stroke Otto Cycle

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Rolls Royce Merlin Engine, photo by Liftam

Constant
volume
heating



1. Intake stroke
2. Compression Stroke
3. Power Stroke
4. Exhaust Stroke

Factors Affecting Power Output of Piston Engines

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- **Fuel to Air ratio**
 - Too rich and combustion may not be complete
 - Too lean and combustion might not take place
- **Max RPM**
 - Increasing RPM will increase power output, but there are limits
 - Max values for typical engines are 2200 to 3500 RPM
- **Temperature**
 - At higher air temperatures (hot day) the SHP will decrease
- **Altitude**
 - As altitude increases, power output decreases

Altitude Effects on Power Output

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- **Charge per stroke:** Quantity of air introduced to cylinder controls amount of heat released
 - Depends on the intake pressure, also called the manifold absolute pressure (MAP)
 - Decreases with altitude
 - Supercharging can increase the MAP and compensate for altitude. Air is compressed by an air-pump before entering the cylinders
- **Combustion**
 - Sufficient quantity of air needed for complete burning
 - Since density decreases with altitude, power decreases with altitude for a given throttle setting
 - For non-supercharged engines:

$$\frac{SHP_{alt}}{SHP_{alt=0}} \approx 1.132 \frac{\rho_{alt}}{\rho_{alt=0}} - 0.132$$

Momentum Theory

- From Momentum theory, it can be shown that thrust is:

$$T = \dot{m}(V_e - V_0)$$

- The power added to the flow is the change in kinetic energy:

$$P = \dot{m}\left(\frac{V_e^2}{2} - \frac{V_0^2}{2}\right)$$

- Propeller efficiency is the ratio between useful power (thrust * velocity) and the total power added to the flow.

$$\eta_p = \frac{TV_0}{P} = \frac{\dot{m}(V_e - V_0)V_0}{\frac{\dot{m}(V_e^2 - V_0^2)}{2}} = \frac{2V_0}{V_0 + V_e} = \frac{2}{1 + \frac{V_e}{V_0}}$$

V_e : exit velocity
 V_0 : free stream velocity
 p : exhaust pressure
 P_∞ : free stream pressure
 A : Disc area
 \dot{m} : mass flow rate

Momentum Theory (cont.)

- To keep efficiency high, it is desirable to keep induced velocity low

$$\eta_p = \frac{TV_0}{P} = \frac{\dot{m}(V_e - V_0)V_0}{\frac{\dot{m}(V_e^2 - V_0^2)}{2}} = \frac{2V_0}{V_0 + V_e} = \frac{2}{1 + \frac{V_e}{V_0}}$$

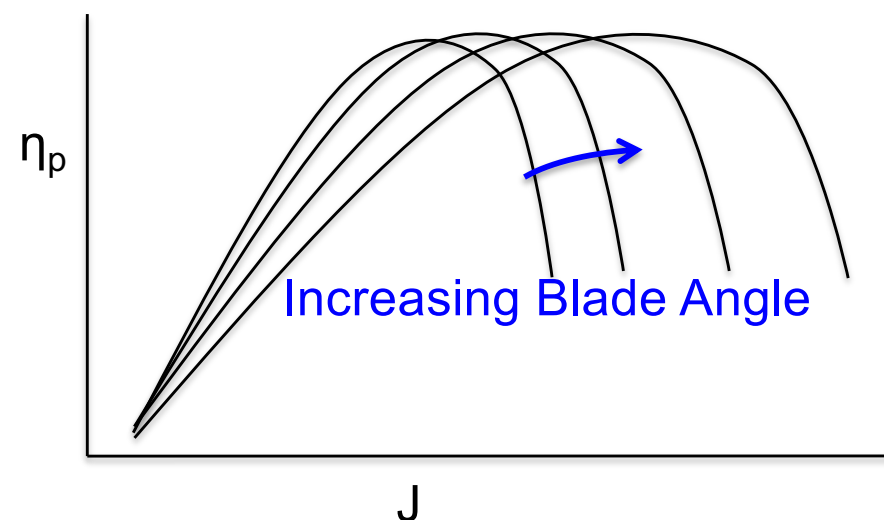
- To keep induced velocity low, need to keep the disc loading (T/A) low
- To keep T/A low, need to make A large, which means a large diameter propeller.
- But size of propellers are constrained:
 - Large tip speeds
 - Ground clearance issues
 - Structural issues

V_e : exit velocity
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Propeller Efficiency

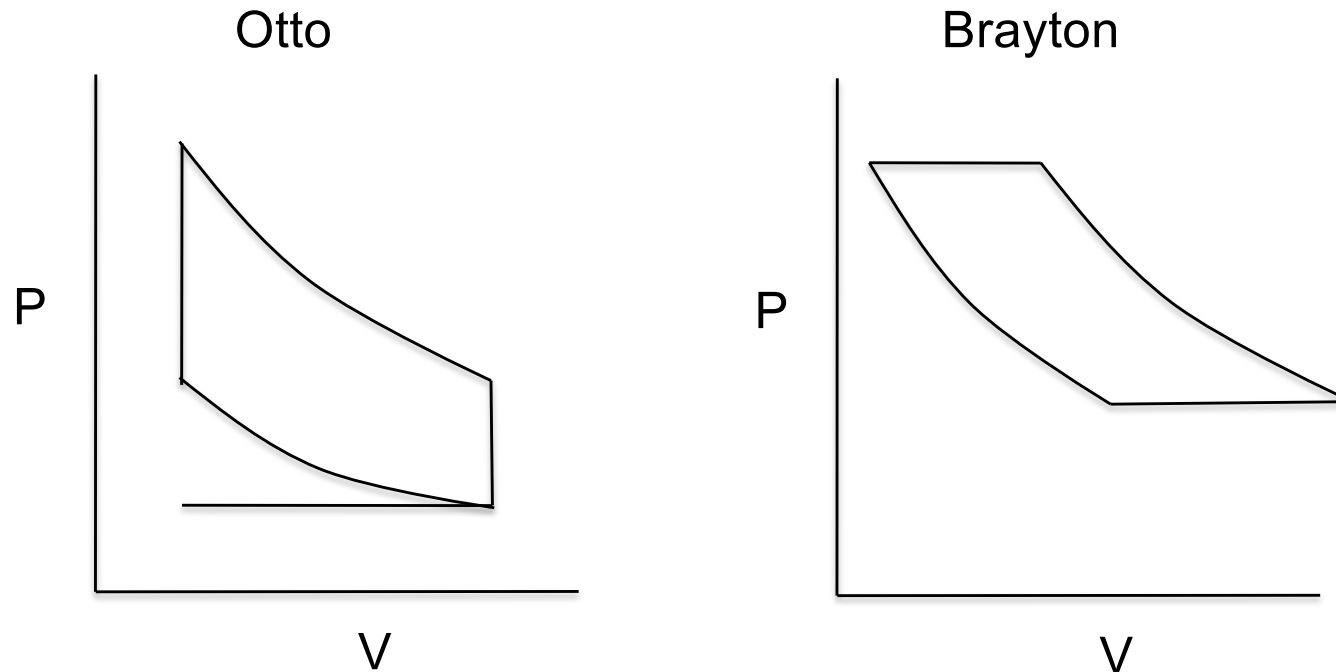
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- **Advance Ratio (J):** ratio between the aircraft velocity and the rotational velocity of the propeller
- **For different advance ratios, there exists an optimal blade angle to maximize efficiency.**
 - Some aircraft use variable pitch props to keep efficiency high for different flight conditions
- **Other factors to consider:**
 - Airfoil and aspect ratio of blade. Higher aspect ratio more efficient but requires larger diameter propeller for same area
 - Number of blades: increasing # of blades reduces load on each and allows for lower overall prop rotation. But also leads to more interference, and more blades is harder to balance
 - Propeller efficiency decreases rapidly at transonic speeds because of wave drag



Piston Engines vs. Turbojets

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- **Piston engines are related to the Otto Cycle**
 - Heat (combustion) added at constant volume
- **A turbine engine is described by the Brayton Cycle**
 - Continuous flow of working gas
 - Burning occurs at constant pressure

Turbojet Overview

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- **Intake funnels air into the engine and slows it down. In general, flow is subsonic before entering compressor**
- **Compressor made up of series of rotating and stationary blades (stators) that heat and compress the air before entering combustion chamber**
- **Combustion chamber continuously burns fuel with the compressed air**
- **Hot gases from combustion spin the turbine like a windmill, extracting power from the flow which is used to drive the compressor**
- **Nozzle accelerates the flow such that it exhausts to atmosphere at a high speed**
- **Unlike piston engines, jet engines produce thrust directly. For a constant throttle setting, how does a jet engine's thrust and power vary with velocity?**

Turbojet Overview (cont.)

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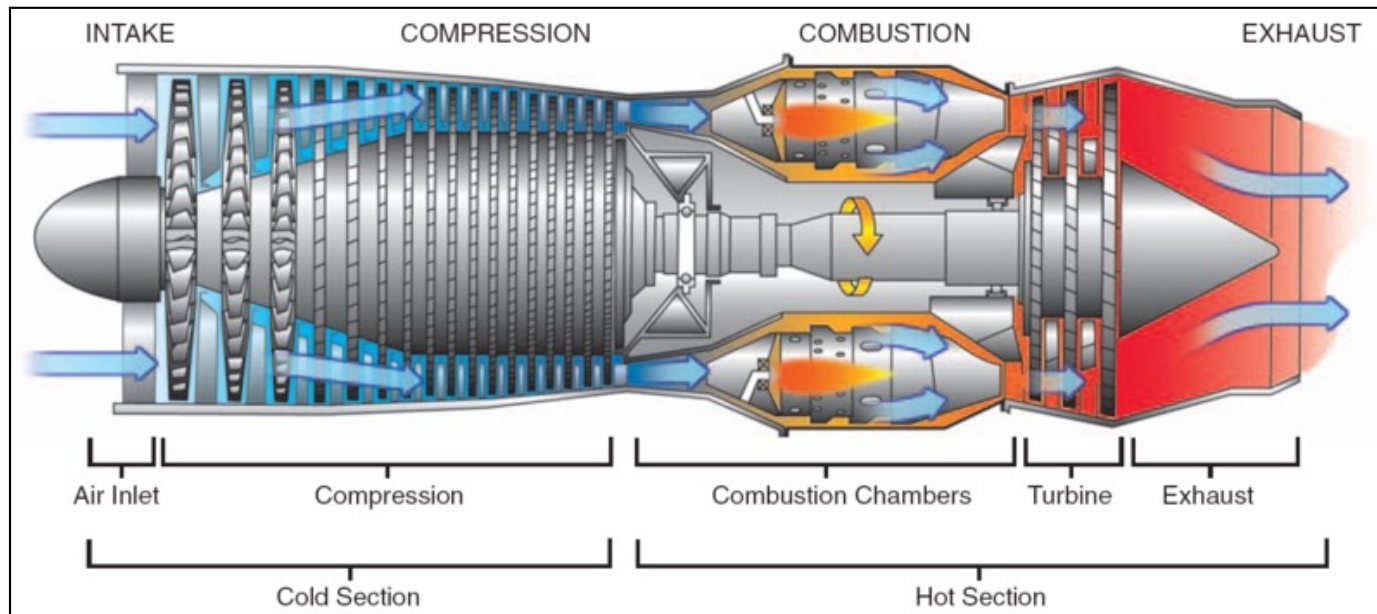


Image Courtesy of FAA

$$F_{thrust} = \dot{m}(V_e - V_\infty) + (p_e - p_\infty)A_e$$

V_e : exit velocity
 V_∞ : free stream velocity
 p_e : exhaust pressure
 P_∞ : free stream pressure
 A_e : Exhaust Area
 \dot{m} : mass flow rate

Propulsive Efficiency

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- **Propulsive efficiency:** ratio between the work done on the aircraft and the energy imparted on the engine airflow
- **Work done on aircraft** is the net thrust multiplied by the aircraft speed
- **Energy imparted on airflow** is the work done on the aircraft plus the energy wasted in the exhaust

$$\eta_{propulsive} = \frac{V_{\infty} \left[\dot{m}(V_e - V_{\infty}) + (p_e - p_{\infty})A_e \right]}{V_{\infty} \left[\dot{m}(V_e - V_{\infty}) + (p_e - p_{\infty})A_e \right] + \frac{1}{2} \dot{m}(V_e - V_{\infty})^2}$$

Assuming nozzle
exhaust fully expands
to atmospheric
pressure...

$$= \frac{V_{\infty} \dot{m}(V_e - V_{\infty})}{V_{\infty} \dot{m}(V_e - V_{\infty}) + \frac{1}{2} \dot{m}(V_e - V_{\infty})^2} = \frac{2V_{\infty}}{V_{\infty} + V_e}$$

- **At low flight speeds, the efficiency is low.**
- **Efficiency can increase at higher speeds**

Turbofan

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- A turbofan consists of a ducted fan and a turbojet engine behind it that powers the fan
- Part of the air goes through the fan and into the engine to be ignited. The rest bypasses the engine
- For high bypass engines, the majority of the thrust is produced by the air that bypasses the engine
- In general, for a given thrust, it is more efficient to move a lot of air at a lower exhaust speed, than to move a small amount of air at a higher speed
- Turbofans have a higher propulsive efficiency than turbojets for this reason, which is why most jet engines today are turbofans
- Intake duct slows airflow before reaching fan blades. This allows turbofans to operate at higher speeds than turboprops

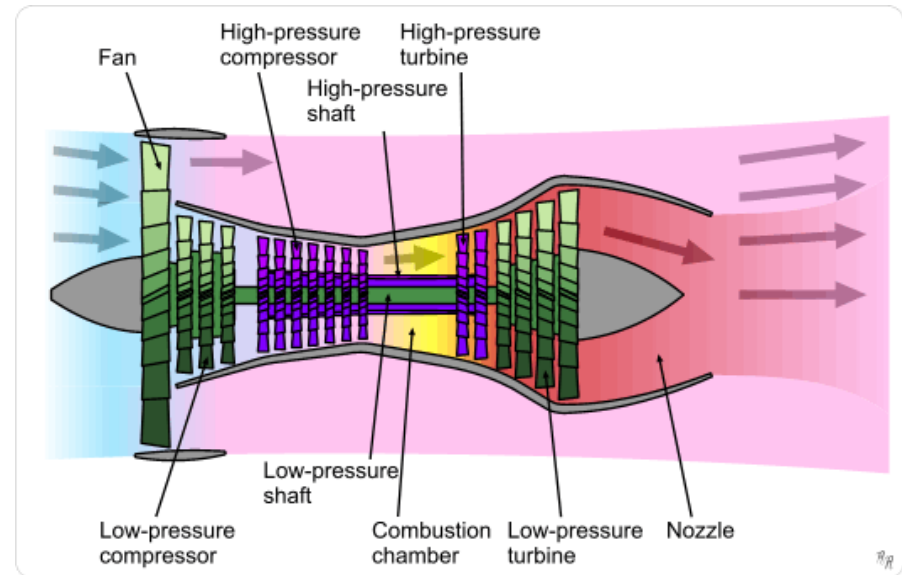


Image Created by K.Aainsqatsi

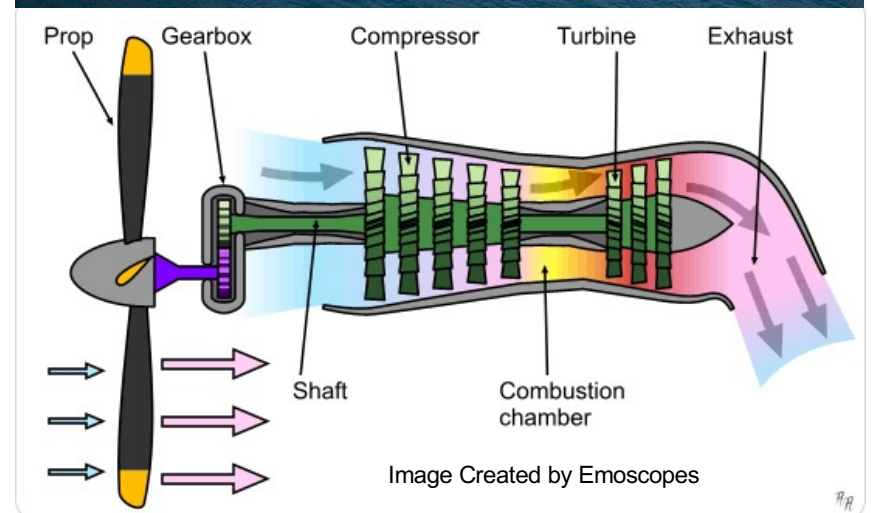
Bypass Ratio =

$$\frac{\text{mass flow rate through fan}}{\text{mass flow through turbine}}$$

Turboprop

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- Turbojet designed to drive a propeller
- Turboprops have a high propulsive efficiency, but since propellers must operate at subsonic inlet speeds, only viable at moderate speeds
- Popular among smaller commuter aircraft and military transport aircraft



Propfans

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- **Propfans attempt to combine the speeds and performance of a turbofan with the fuel efficiency of a turboprop**
 - Potentially more efficient than turbofan
 - Propeller blades are swept back to reduce wave drag
 - Very noisy



Electric Aircraft

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- Improvements in battery energy density has started to make electric aircraft more practical
- Extra 330 LE
 - 2-seater aerobatic aircraft
 - 15-20 min flight time
- Eviation Alice
 - Electric commuter aircraft
 - First flight in September 2022
 - Designed to fly 440 nmi at 250 kts
 - 820 kW-h battery pack expected to make up almost 60% of the total aircraft weight



References

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