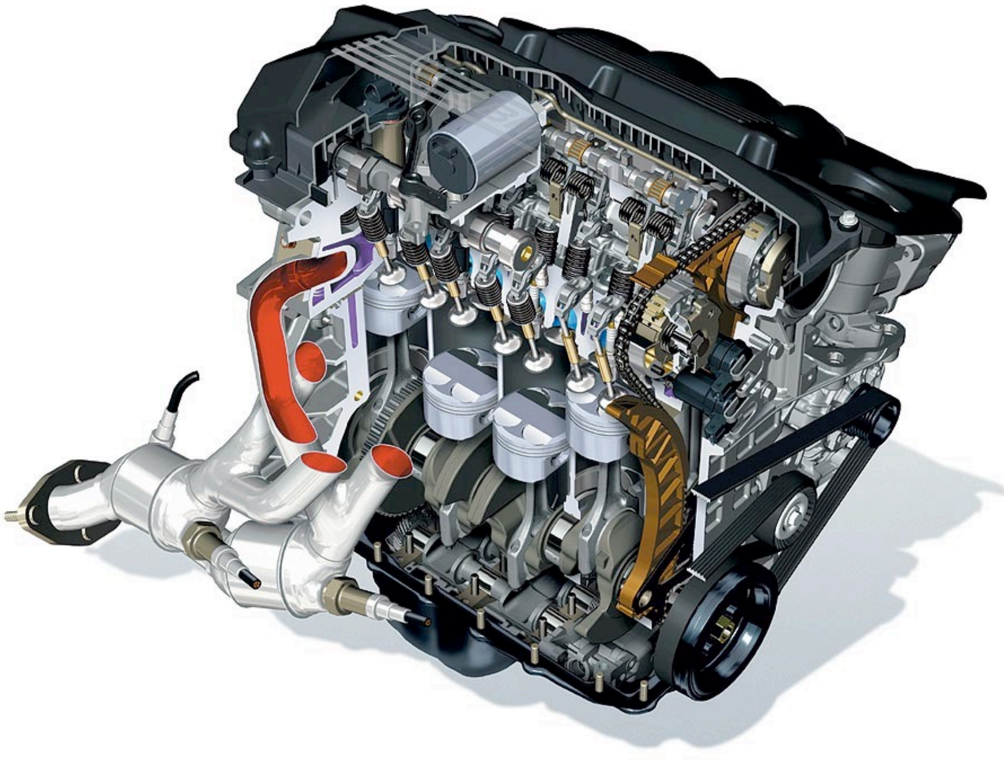
Chapter 1:
General Introduction



Learning Objectives of Chapter 1 - Introduction

- ⇨ know the names and functionalities of the main mechanical **components**
- ⇨ know the **operating principles** of Internal Combustion Engines
- ⇨ know the **flows** (5) acting during operation
- ⇨ know the different types of usual engines : 2-stroke, 4-stroke, Diesel, Otto…

Content Chapter 1

- **Introduction**
- Description of the main components
- Operating principle
  - Mechanics of the reciprocating engine
  - Engine cycles
  - Flows inside reciprocating engines
- Classification
  - Reciprocating engine families
  - Kinematics of the piston

Introduction

Engine = generator of mechanical energy (torque, work)

- System **inlet** ⇒ 1 <u>energy source</u>

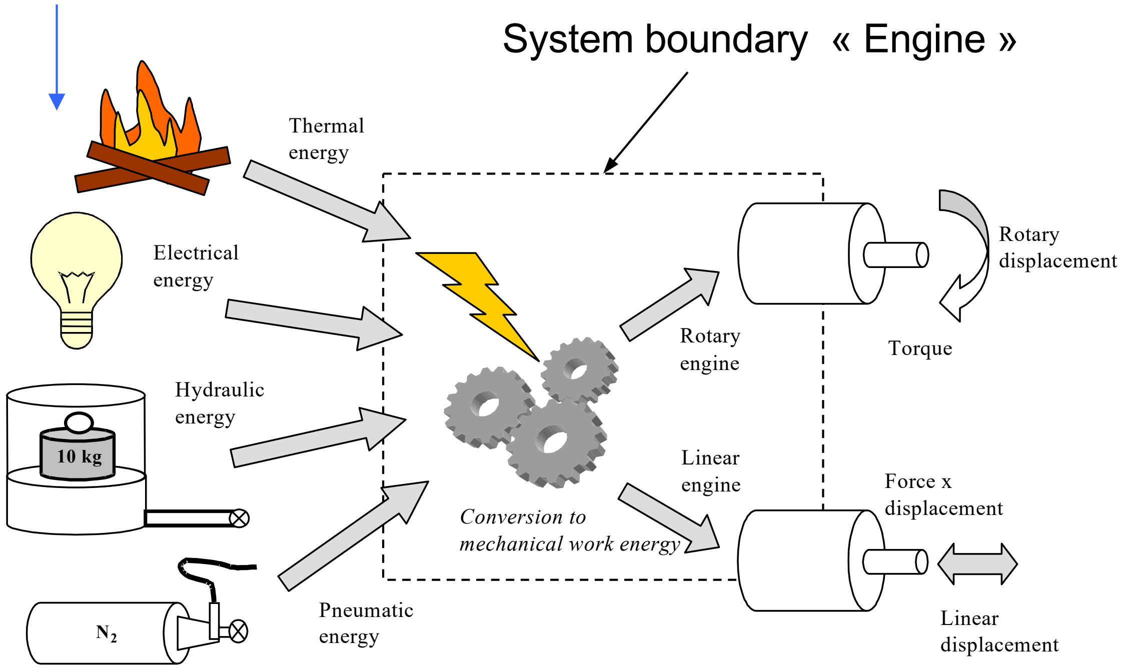
  Example :

  ⇒ **Thermal**

  ⇒ Electrical

  ⇒ Hydraulic

  ⇒ Pneumatic

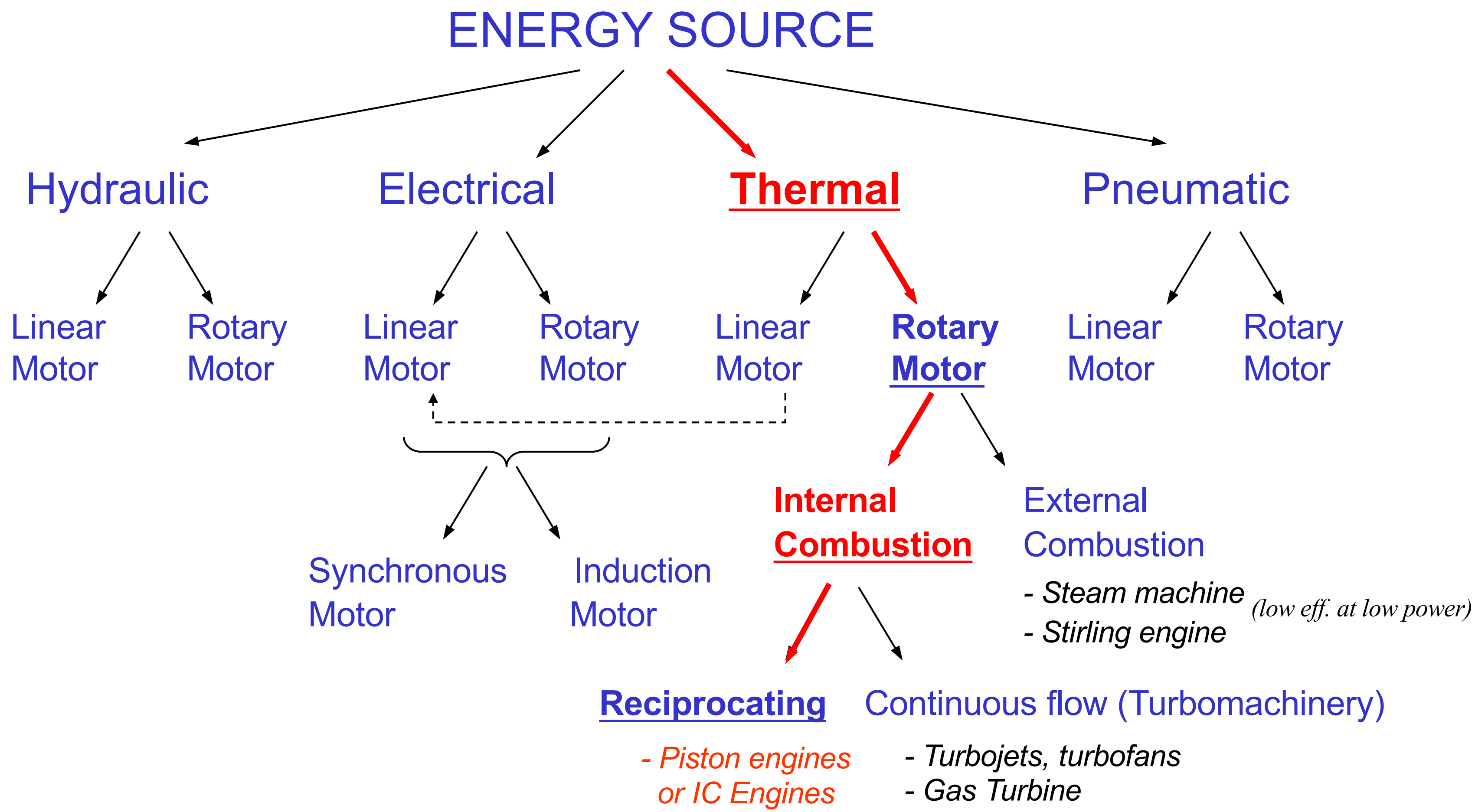


- System **outlet** ⇒ 1 <u>mechanical work</u> (E_{mec}) ⇒ *Force* (N) or *Torque* (Nm)

  linear rotary

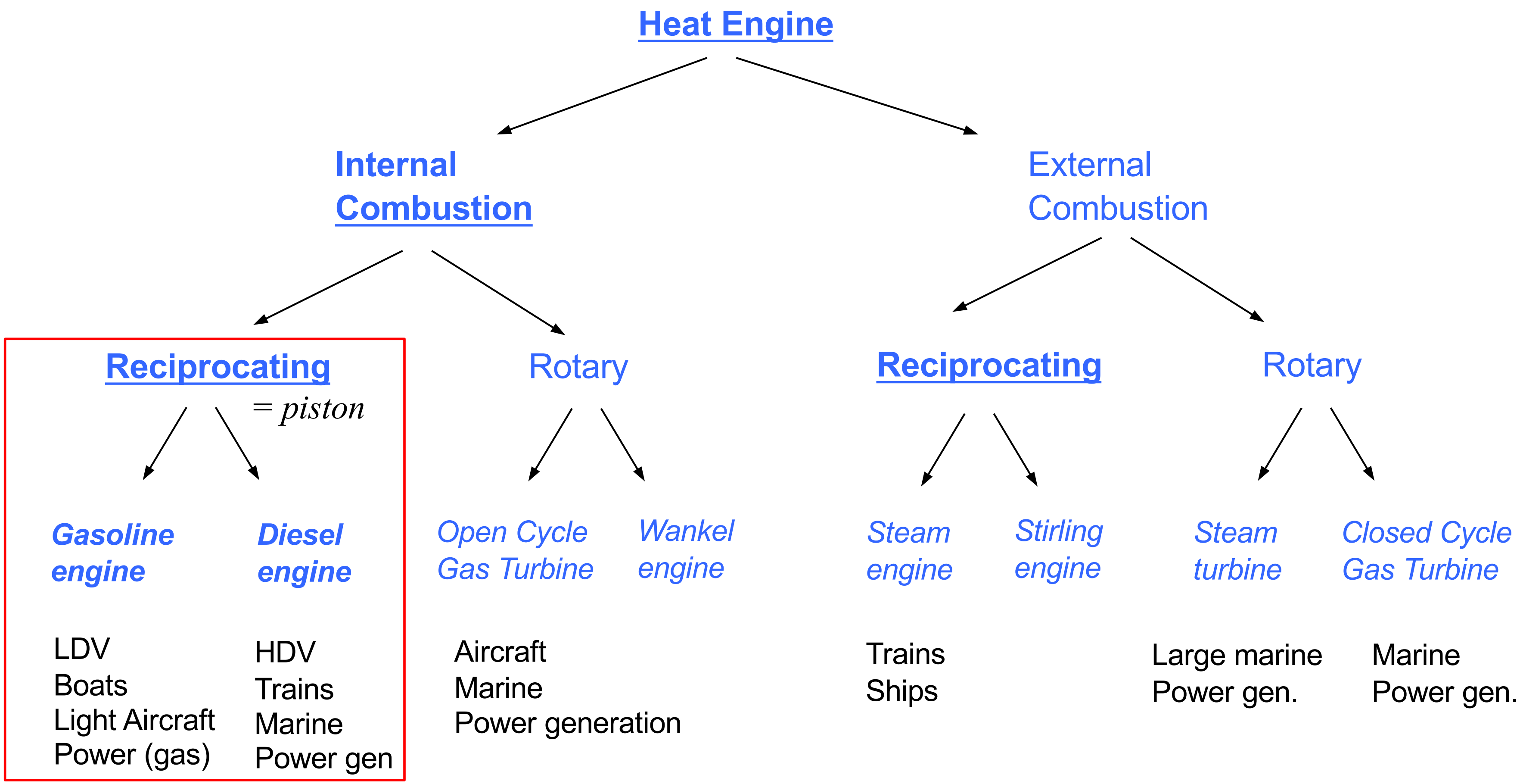
The main requirement is to generate PRESSURE, to push a piston.

Introduction



ICE have no heat exchangers unlike ST, GT cycles => simpler and more efficient

Course focus = thermal reciprocating ICE *or* piston engines



Advantages ICE	Disadvantages ICE
Average T is lower than in GT, ST, but max T is high for a short time => higher thermal efficiency	Vibrations
For high thermal efficiency, (**average**) working **pressure** stays moderate => lower weight-to-power ratio than ST cycle => allows downsizing to low power (< 1 kW)	Needs clean (expensive) fuels

Introduction

- **Ranges**

Stroke, Hub   @crankshaft

	No. of cylinders	Bore (ϕ)	(air) displacement per cylinder	Eff. Power [kW]	Speed [rpm]	Length	Mass
Min	1	6 mm	0.16 cm^3	0.02	> 30’000	≈ 4 cm	14 g
Max	≈ 27	> 1 m	> 2 m^3	75’000	≈ 60	> 20 m	> 2000 t

- Application :

⇒ Transport

- Motorcycles, Cars, Trucks, Ships, Railroad, Airplanes, Helicopters

⇒ Electric power

- Generators, Power plants (including cogeneration)

⇒ Machines

- Off-road vehicles, agricultural, home use

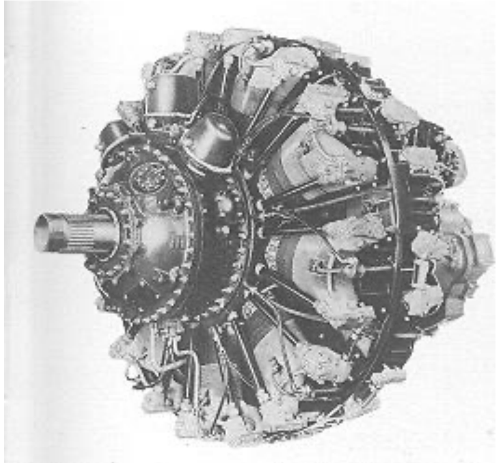
⇒ *etc…*

Application examples

hand tools

4 cm

small plane



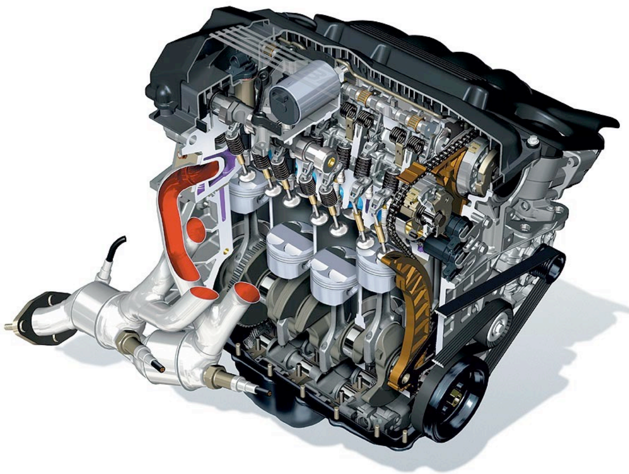
Pratt & Whitney Engine

(18 cylinders, 45.9 L, 2500 hp)

motorbike

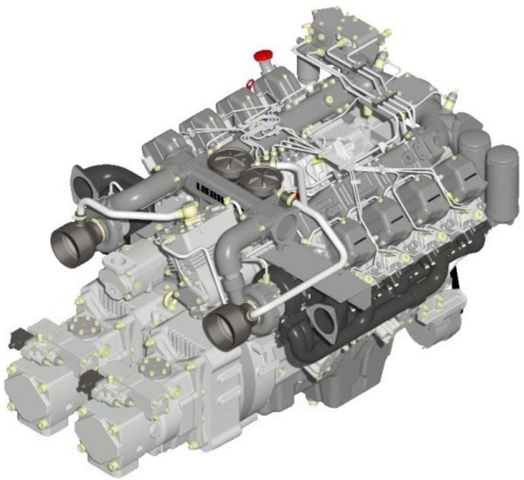
DUCATI 996R Engine

(2 cylinders,996 cm^3,123HP



BMW 318i Engine (4 cylindres, 1.8L, 125 hp)

car

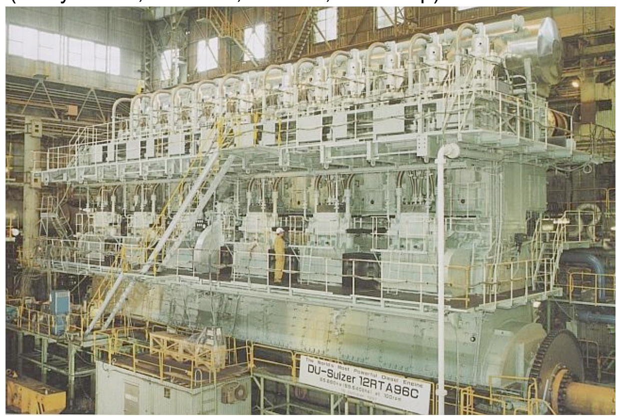


Liebherr *Engine* D9408 (V8, 16L, 440 kW @ 2100 1/min)

'small' cogeneration

SULZER-WARTSILA Engine

(12 cylinders, 2-Stroke, 21845L, 89640 hp)



20 m

Large cogeneration/power

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  - Engine Cycles
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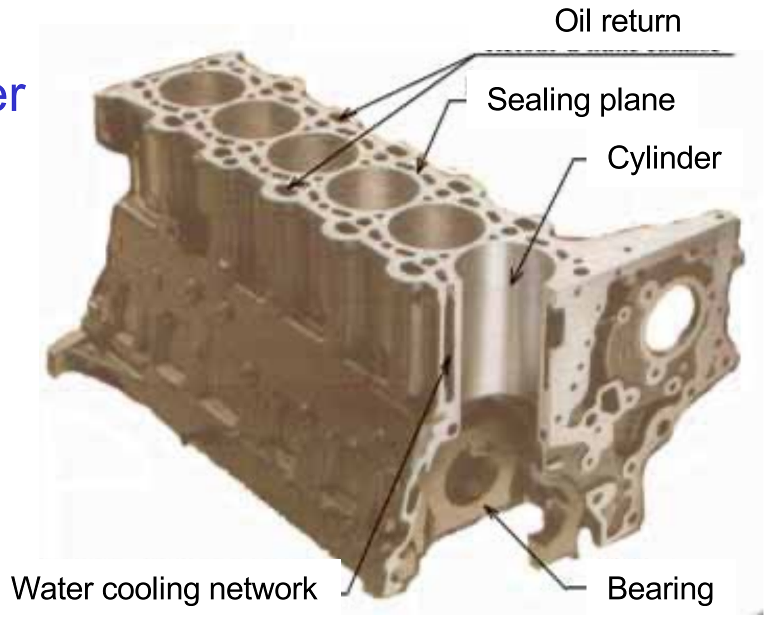
Glossary of component terms in other languages

ENGL	FR	D	IT	ESP	NL
2-stroke	à 2 temps	2-Takt	a due tempi	de dos tiempos	2-takt
4-stroke	à 4 temps	4-Takt	a quattro tempi	de cuatro tiempos	4-takt
bearings	paliers	Lager	cuscinetti	rodamientos	lagers
bore	alésage	Bohrung	alesaggio	diametro	boring
camshaft	arbre à cames	Nockenwelle	albero a camme	arbol de levas	nokkenas
connecting rod	bielle	Pleuelstange	biella	biela, varilla	drijfstang
crankcase	carter	Kurbelgehaüse	carter, basamento	carter	carter
crankpin	maneton	Kurbelzapfen	peron di manovella	rodaje del cigüenal	kruktap
crankshaft	arbre villebrequin	Kurbelwelle	albero motore, a gomito	cigüenal	krukas
cylinder head	culasse	Zylinderkopf	testata del motore	culata	cylinderkop
flywheel	volant d'inertie	Schwungrad	volano	volante	vliegwiel
piston	piston	Kolben	pistone	piston	piston
scavenging (port)	(port à) balayage	Spül(öffnung)	luce di lavaggio	lumbrera de barrido	spoel (poort)
throttle valve	vanne papillon	Drosselventil/klappe	valvola a farfalla	valvula de mariposa	gasklep
torque	couple	Drehmoment	coppia, torsione	par, torsion	koppel, torsie, draaimoment

Main components

1. Cylinder Block

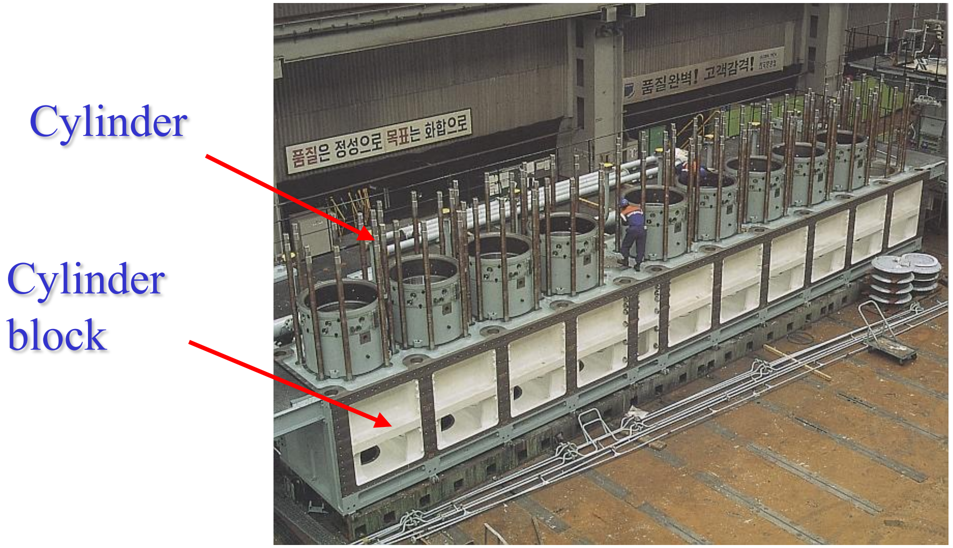
- Joins all components together
- Basis for the fitting of auxiliary components (pumps, AC, alternator,…)
- Fitting of the gearbox
- Fitting of engine supports (=fuel/water/oil pumps,..)
- Integrating the crankcase
- Defines total cyl. volume, thus power
- Cast iron or aluminium



Main components

2. Cylinders

- usually directly bored in the cylinder block; *or* else a separate part from the cylinder block (for big cylinders)
- task 1 : guide the (vertical) piston motion
- task 2 : heat release function



Main components

3. Piston

= moving boundary of the combustion system

- transmits the gas force
- undergoes huge mechanical & thermal stresses !

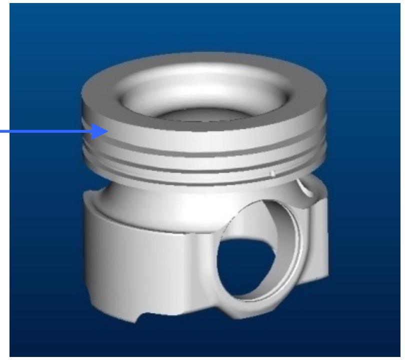
P_{max} : ⇒ ≈ 70 bars (naturally aspirated gasoline engines: inlet at P_{atm})

⇒ ≈ 220 bars (turbocharged Diesel engines)

- maintains the piston rings

3 rings: 1. heat protection 2. sealing 3. oil film scraping

Usually:



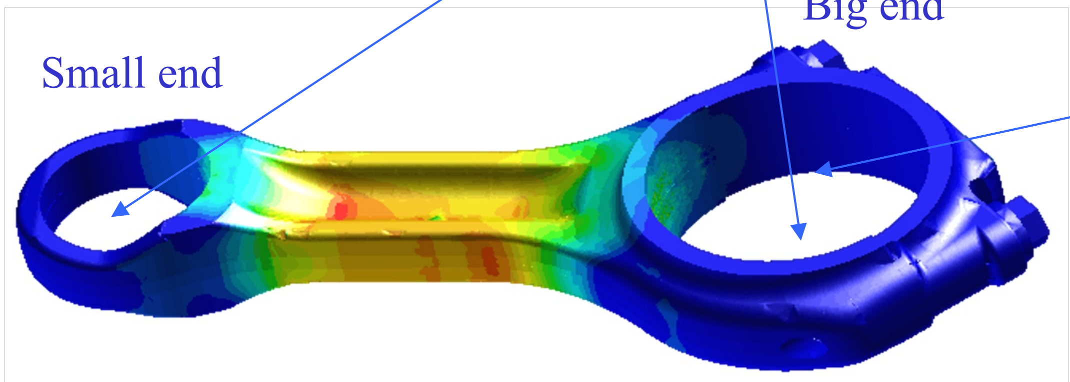
Large 2-stroke

Piston of a Wankel **rotary** engine (exceptional case)

4. Connecting rod

tranmits the gas force on the piston to the crankshaft

- connects the piston to the crankshaft
- under v. high mechanical cycle fatigue
  - $\sigma_{compressive}$ (due to gas pressure forces P_{gas})
  - $\sigma_{tensile}$ (due to inertial forces $F_{inertia}$)
- small end: attached to the piston pin
- big end: connected to the crankshaft



CFD, structural mechanics, stress field, T field

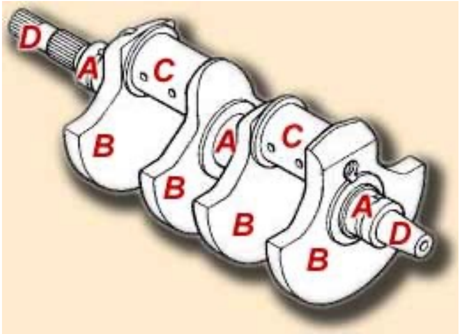
Assembly Piston – Ring – Connecting rod

3000 rpm = 50 Hz => every 20 ms
a compression/tension cycle !

Main components

5. Crankshaft

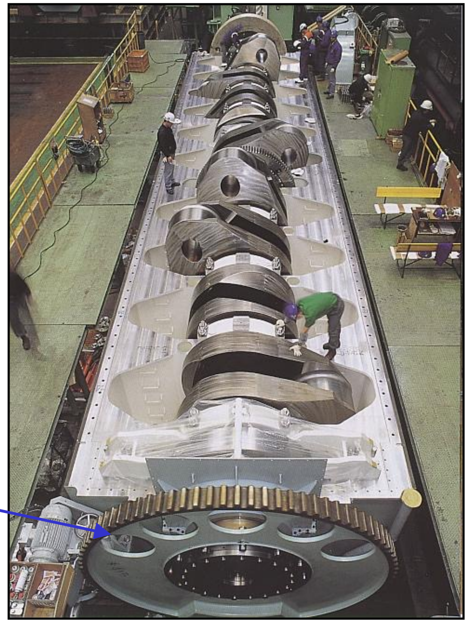
- Enables the transformation of the linear oscillating motion of the piston into rotary motion on the power shaft (wheels).



- main bearings ⇒ (**A**)
- big-end bearing ⇒ *crank pin* (**C**)
- counterweight ⇒ (**B**)
- engine outlet torque ⇒ *shaft* (**D**)

6. Flywheel (or inertia wheel)

- used as storage device for kinetic energy
- Task 1 : reduces the rpm fluctuations
- Task 2 : enables the engine start-up



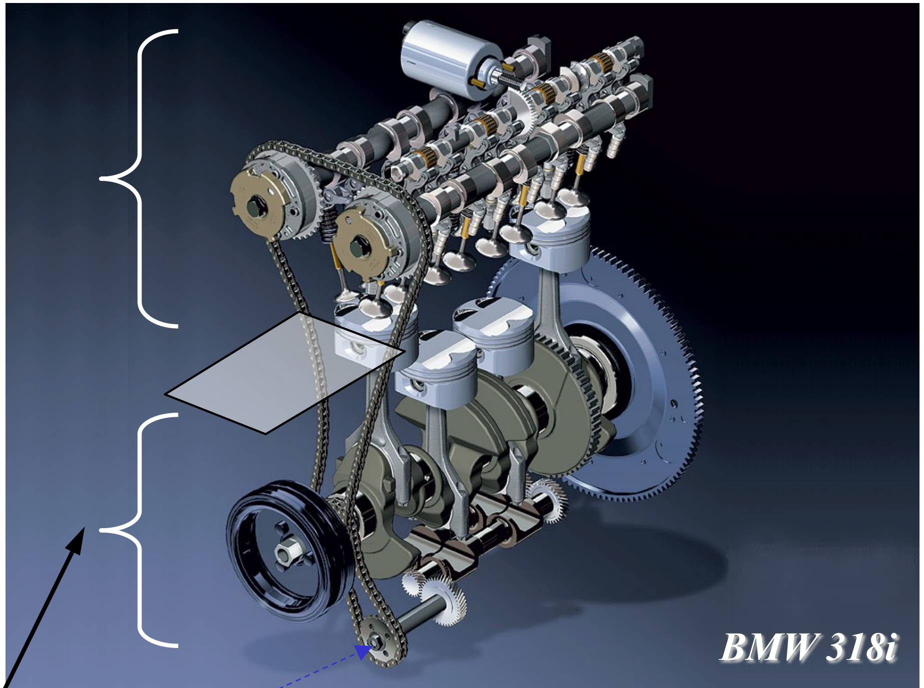
Main components – overview so far (bottom engine)

Top engine

- Cylinder head (p.17)
- Valve train system (p.18)

Bottom engine (p.11-15)

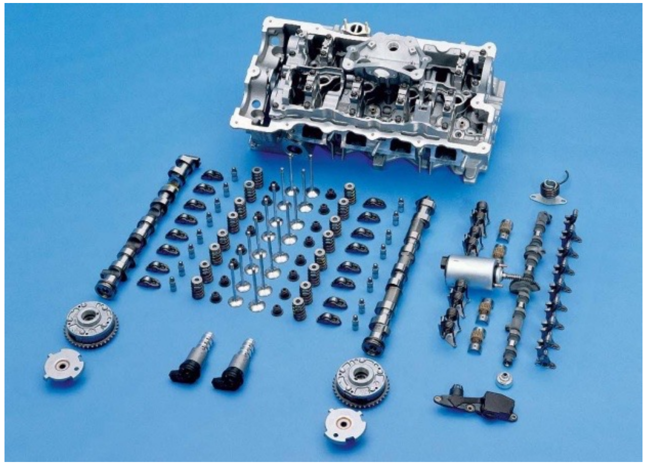
- Cylinder block
- Piston
- Connecting rod
- Crankshaft
- *Balancer shaft (opt.)*
- Flywheel
- Oil pump

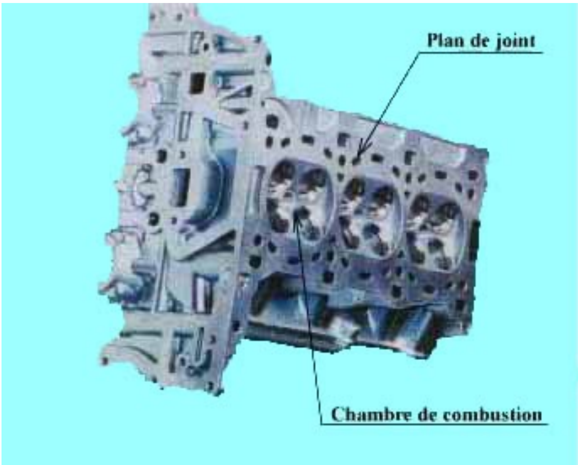


6 in-line cylinder

Main components – top engine

7. *Cylinder head:* = seat of
   - Intake and exhaust ports (2-stroke)
   - Valve train system (pp.18, 20,...) (4-stroke)
   - Injection system (fuel, air)
   - Ignition system (e.g. spark; not with Diesel)
   - Cooling of hot components
   - Gives the geometry (design) of the combustion chamber (=> controls the combustion, hence the engine and the associated polluting emissions)
   - Head gasket (for gases (air, fuel, exhaust), water and oil sealing)

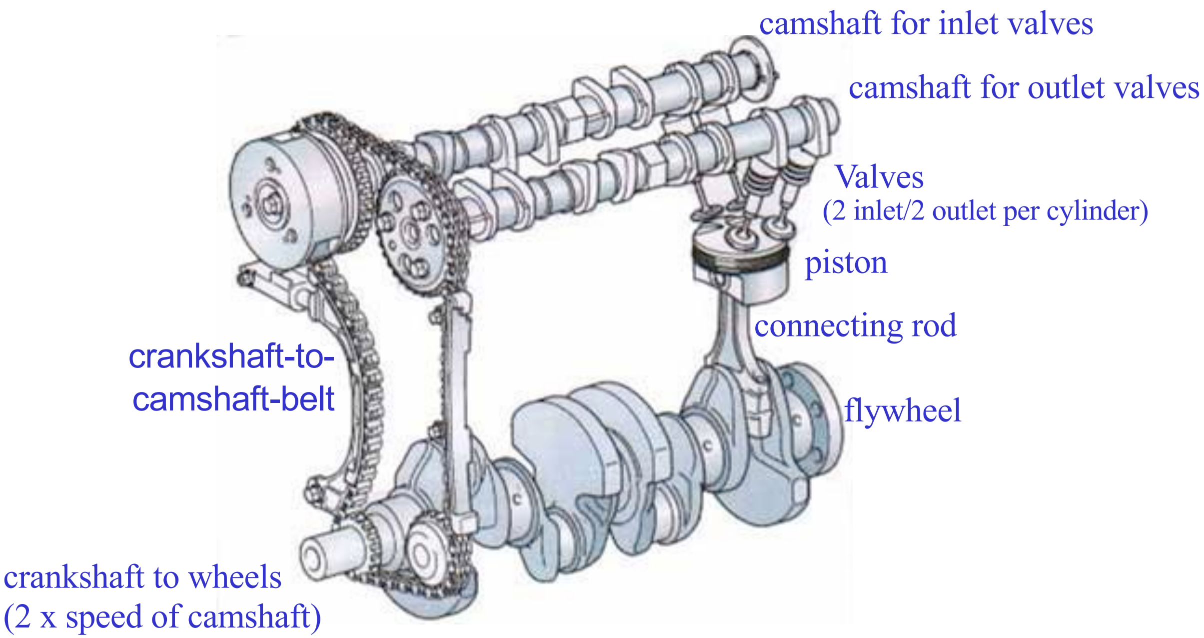




Main components – top engine

8. Valve train system (part of *7. the Cylinder head*)

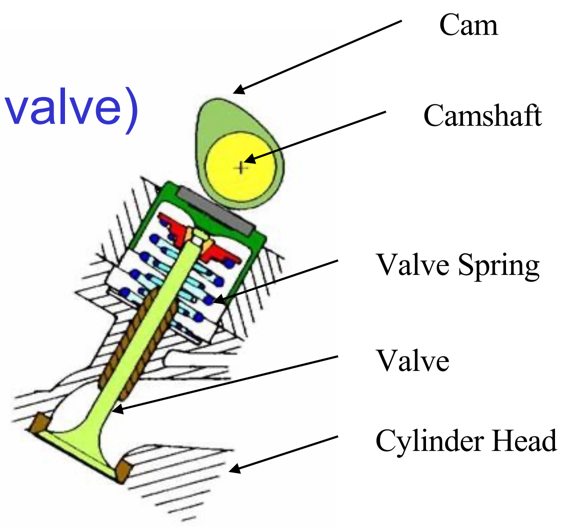
- opening/closing via camshaft (4-stroke, p.19) *or via* ports (2-stroke, p.20)
- valves (incl. springs) *or* orifices
- distribution control (rocker arm, pushrods, lifters) – p. 21
- driving of auxiliaries & accessories – p. 21
- *variable* valve driving system (optional) – p. 22-23

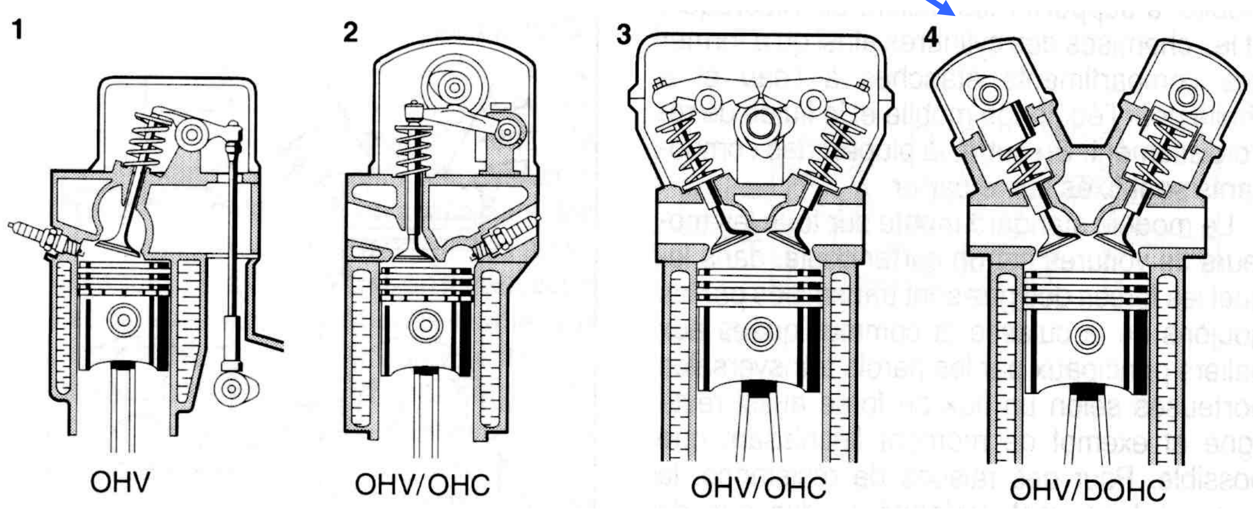


Main components – top engine

9. Camshaft

- ensures the induction of fresh air (intake valve)
  and the expulsion of combustion gases (exhaust valve)
  ⇒ given by the cam **profile**
- Camshaft position:
  - Lateral : **(1)**
  - Overhead camshaft OHC (end pivot rocker) : **(2)**
  - Overhead camshaft (center pivot rocker) : **(3)**
  - Overhead camshaft (direct-acting) : **(4)**



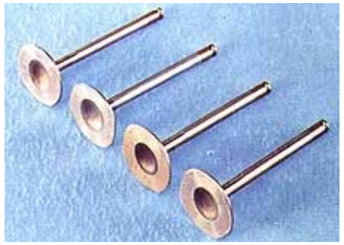


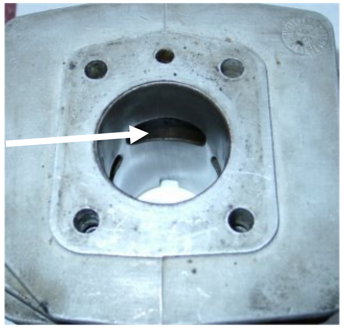
OHV: overhead valve

Main components – top engine

10a. Valves

- ensure the fluid transfer (air)
- seat of gases sealing
- Mechanical return system
  - with spring
  - with cam (desmodromic)
- Pneumatic valve timing



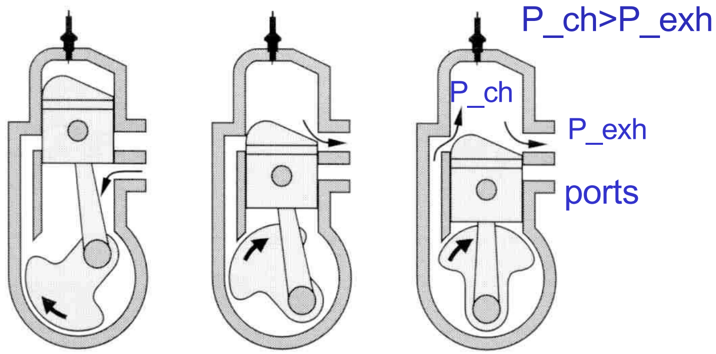


Desmodromic (Ducati) –
valves bound to the camshaft to avoid gripping of springs

10b. Ports (scavenging ports)

- =alternative to the camshaft driving system
- scavenging ports in the cylinder
- available only on **2-Stroke** engines
- slip of fuel / exhaust => efficiency↓, emissions↑

(blue smoke; lubricant oil)



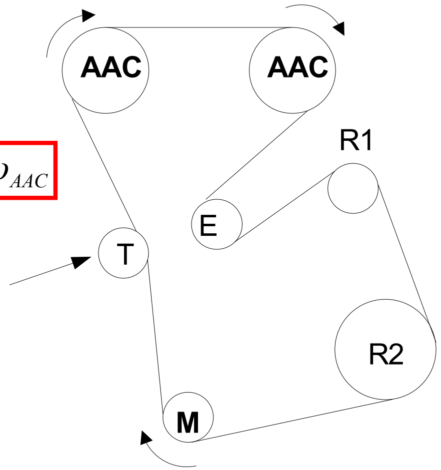
2-Stroke engine with compression in crankcase

Main components – top engine

11. Distribution control:

- To drive the camshaft system
  - ⇒ by chain *or* belt (incl. tensioner)
  - ⇒ by gear
- To drive auxiliaries and accessories
  - ⇒ Pumps : water, oil, fuel
  - ⇒ Alternator (=>on-board electricity)
  - ⇒ Compressors : air, air-conditioning

$$\omega_M = 2 \cdot \omega_{AAC}$$



M : Crankshaft

AAC : Camshaft

R1 : Alternator

R2 : Compressor

E : Belt idler roller

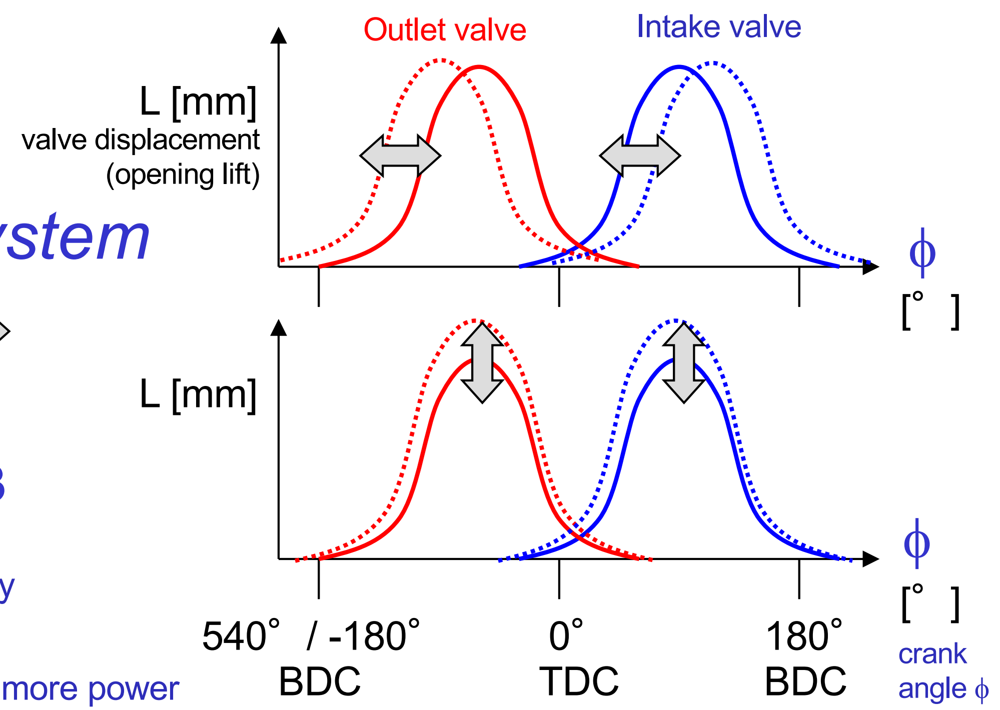
T : Belt tensioner roller

(Opt.) Variable valve timing system

- phase shift of the cam profile ⇔
- variable valve lift ⇕
- phase shift + variable lift, cf. p.23

⇔ time of fuel injection start => combustion efficiency

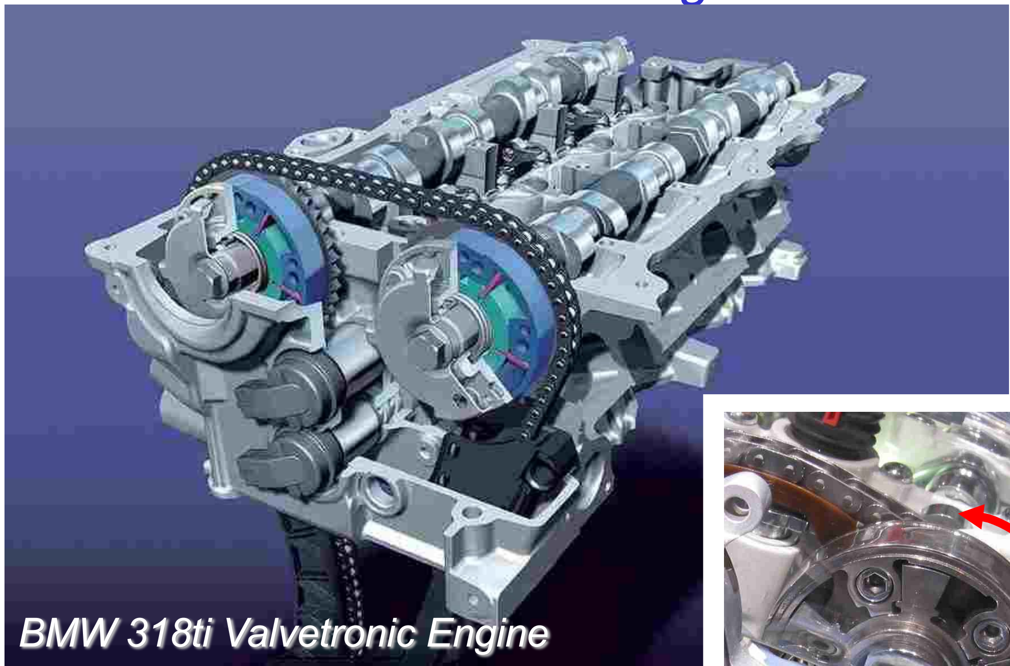
⇕ Duration (=amount) of fuel injection, air intake => more power



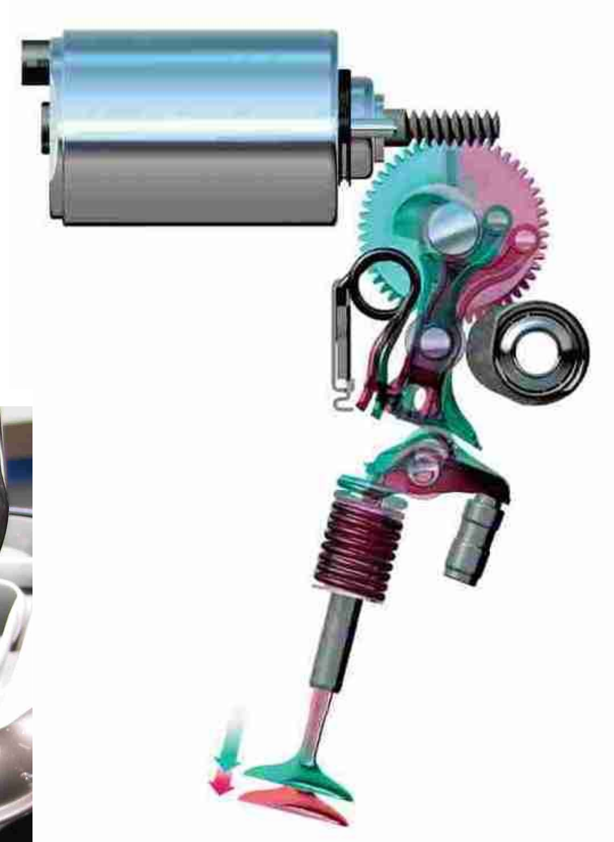
Main components – valves

- *Variable valve timing system: examples*

Variable Valve Timing

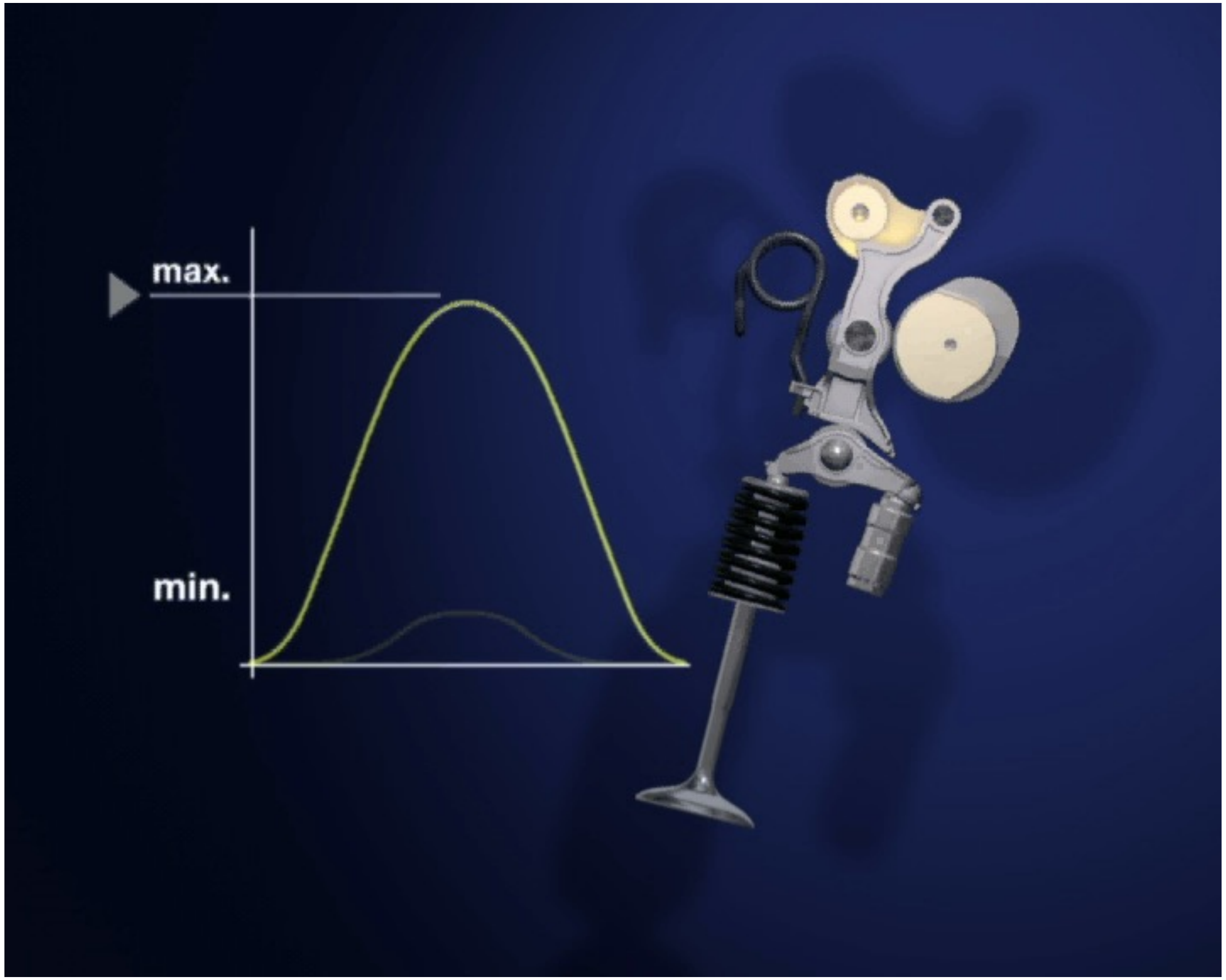


Valvetronic



Main components – valves

- *Variable valve timing system: Valvetronic (BMW)*



3D movie
of the main
components

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Operating principle

- Definitions, Terminology

  D : Bore

  L : Stroke

  R : crank radius ⇒ $R = \frac{L}{2}$

  TDC : Top dead center

  BDC : Bottom dead center

  V_0 : clearance volume ⇒ $V_0 = V_{TDC}$

  V_U : displaced volume ⇒ $V_u = L \cdot \frac{\pi \cdot D^2}{4}$ = swept volume by the piston

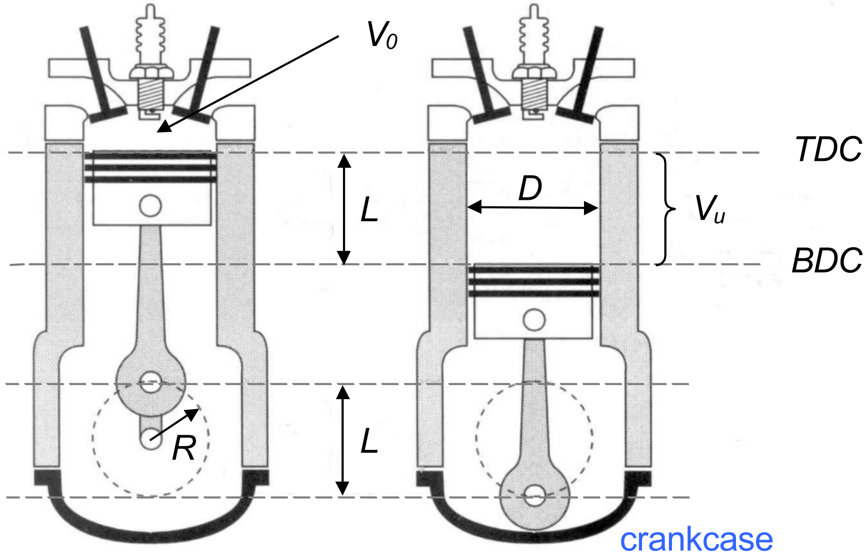
  V_C : maximum cylinder volume ⇒ $V_C = V_{BDC} = V_0 + V_u$

  V_{cyl} : engine displacement ⇒ $V_{cyl} = n \cdot V_u$

  n : number of cylinders

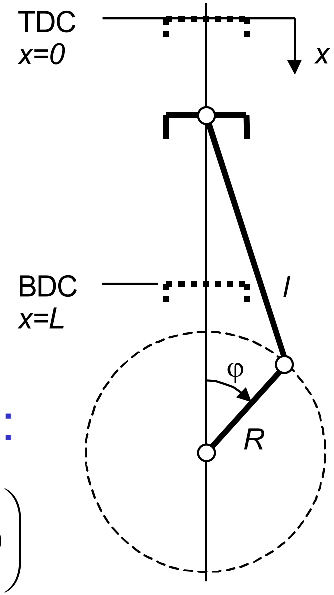
  ε : Compression ratio ⇒ $\varepsilon = \frac{V_C}{V_0} = \frac{V_u + V_0}{V_0}$

  => key for efficiency



Operating principle

- Mechanics of the reciprocating engine



displacement L = 2R

φ : crank angle ($\varphi_{c.a}$) : represents time (motion)

l : connecting rod length

λ : ratio of connecting rod radius/length $\Rightarrow$ $\lambda = \frac{R}{l}$ (0.2-0.3)

$x = f(\varphi)$: equation of piston motion $\Rightarrow$ can be derived to be:

$$x = R \cdot \left(1 - \cos(\varphi) + \frac{\lambda}{2} \cdot \sin^2(\varphi)\right) = R \cdot \left(1 - \cos(\varphi) + \frac{\lambda}{4} - \frac{\lambda}{4} \cdot \cos(2\varphi)\right)$$

ω : angular velocity $\Rightarrow$ $\varphi = \omega \cdot t \quad with \quad \omega = \frac{2 \cdot \pi \cdot N}{60}$ *N* in [1/min]

c : instantaneous piston velocity $\Rightarrow$ $\dot{x} = c = R \cdot \omega \cdot \left(\sin(\omega t) + \frac{\lambda}{2} \cdot \sin(2\omega t)\right)$

c_{mean} : mean piston velocity $\Rightarrow$ $c_{moy} = \frac{2 \cdot R \cdot \omega}{\pi} = \frac{L \cdot \omega}{\pi} = \frac{L \cdot N}{30}$

a : piston acceleration $\Rightarrow$ $\ddot{x} = a = R \cdot \omega^2 \cdot \left(\cos(\omega t) + \lambda \cdot \cos(2\omega t)\right)$

Operating principle

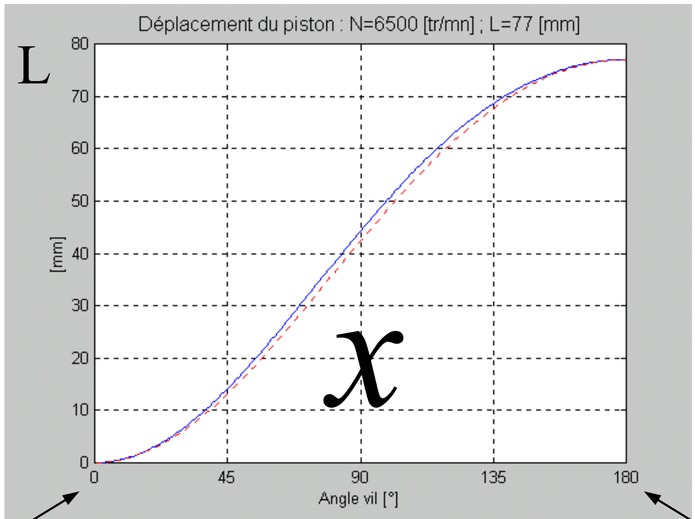
- ## Mechanics of the reciprocating engine

***x*, *c* and *a* depend on λ**

Example : L = 77 mm = 2R (R = 38.5 mm)

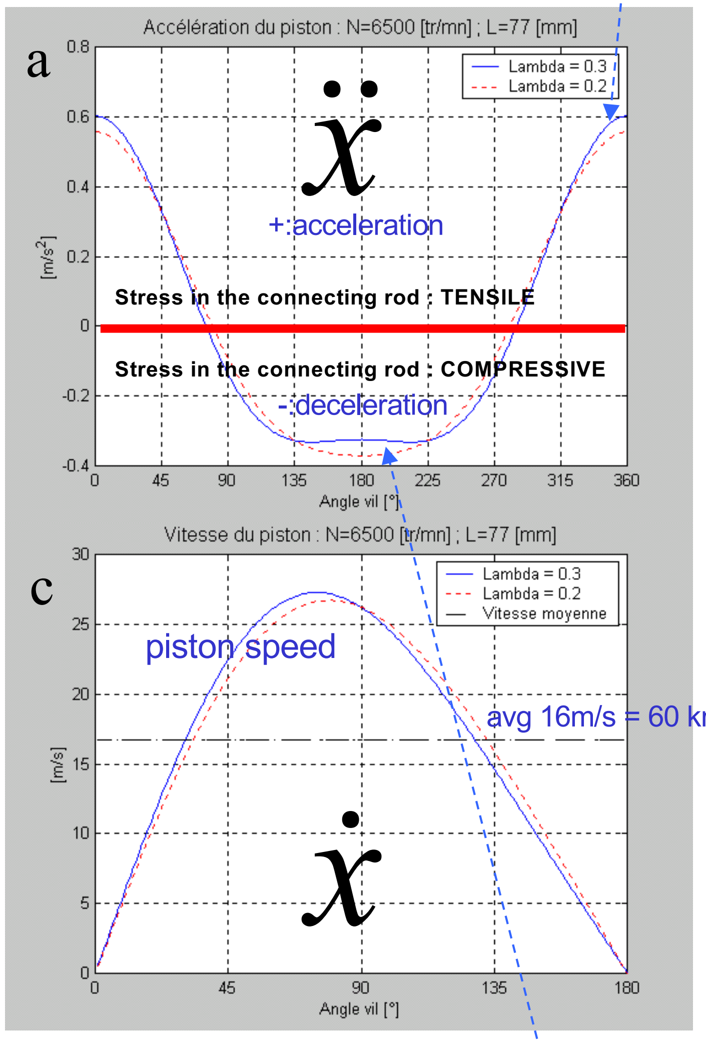
$R = \lambda . l$ $\lambda_A = 0.3 \Rightarrow l_A = 128$ mm

$\lambda_B = 0.2 \Rightarrow l_B = 192$ mm



TDC BDC

max tensile stress at TDC (low load) and high engine speed



max compressive stress at BDC (high load) and low engine speed

Operating principle

- **The cycle in reciprocating engines** (for both 2- and 4-stroke)

  The cyclic operation constantly renews the fresh mixture into the cylinder

  $\Rightarrow$ sequence of successive events called *strokes*

  1) Gas intake : *intake (induction) stroke* (=> takes a certain time)

  - **draw fresh gas into the cylinder**
  - inducted gas: air (Diesel) *or* flammable mixture (air + fuel: Otto)
  - at start: combustion chamber = open system by the **intake** port/valve
    - *open for a very short time only*
  - at end: combustion chamber = closed and sealed system

Operating principle

- The cycle in reciprocating engines

  The cyclic operation constantly renews the fresh mixture into the cylinder

  ⇒ sequence of successive events called *strokes*

  2) Compression of the gases: *compression stroke (**<u>isentropic</u>**)*

  - compression (p) by piston motion towards TDC; fully closed system
    - *(a certain P*$\uparrow$ *is needed to start the combustion process => P*$\uparrow\uparrow$*)*
  - **increase of pressure and temperature** of the working fluid
  - in case the inducted fluid is only fresh air, the fuel injection takes place at the end of the compression stroke (= DIESEL cycle)
  - gasoline (Otto): compression of the mixture air + fuel

Operating principle

- The cycle in reciprocating engines

  The cyclic operation constantly renews the fresh mixture into the cylinder

  ⇒ sequence of successive events called *strokes*

  3) Combustion of the mixture followed by expansion: *expansion / power stroke*

  - combustion starts as soon as the mixture has the suitable conditions for ignition
    - OTTO cycle : ignited by an electric arc (v. fast - homogeneous)
    - DIESEL : auto-ignition (slower – heterogeneous)
  - **heat energy release ⇒ increase in P** (depends on Δu *(internal energy)* and M_F)
  - the high pressure increase of the gases will produce a force on the piston and push it down forcing the crank to rotate ⇒ expansion / power stroke: generates WORK
  - this stroke is the only one which generates a positive work (E_e^+) on the crank

Operating principle

- The cycle in reciprocating engines

  The cyclic operation constantly renews the fresh mixture into the cylinder

  ⇒ sequence of successive events called *strokes*

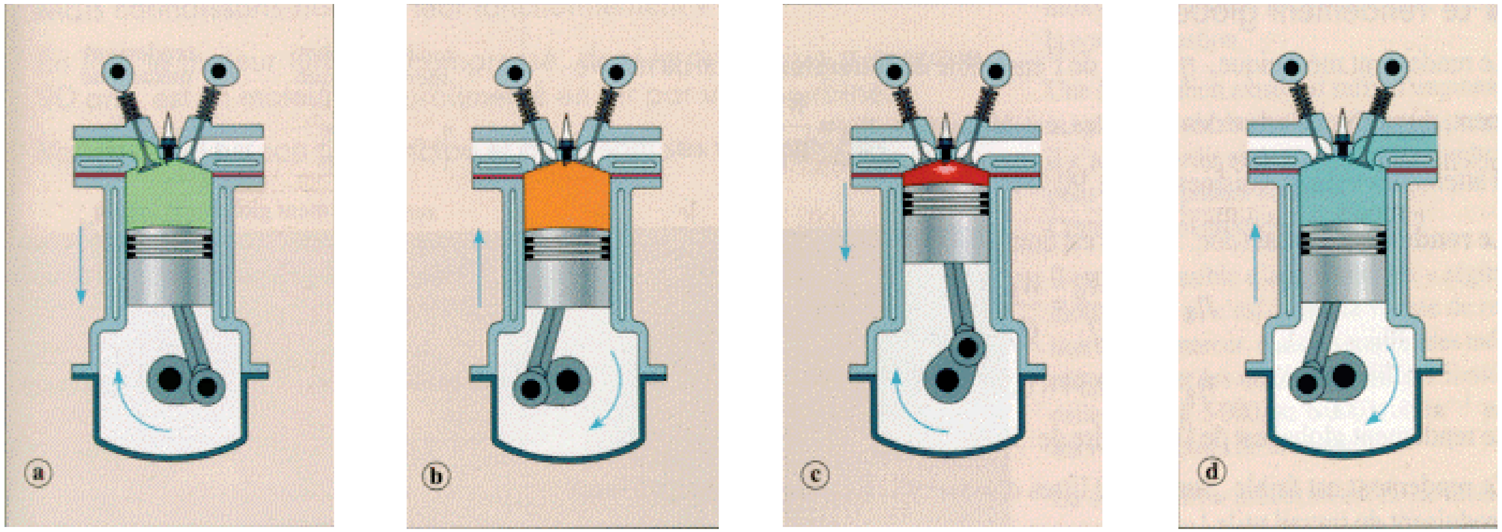
  4) Expulsion of burnt gases: *exhaust stroke*

  - **burnt gases are swept out to renew the working fluid (fresh mixture)**
  - at start: combustion chamber = <u>open</u> system by the **exhaust** valve/port
  - at end: **exhaust** valve closes (and the combustion chamber is reopened at the inlet valve)
  - next cycle starts again ⇒ **intake** stroke, compression stroke, and so on…

3D movie continued (4-stroke)

Operating principle **4-stroke**

- 4-Stroke cycle complete overview
  - operating according to the 4 preceding consecutive strokes:



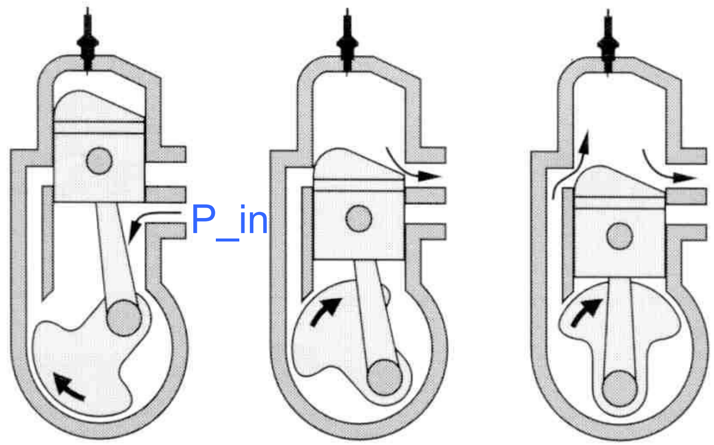
Intake | *Compression* | *Combustion + Expansion* | *Exhaust*

  - each cylinder requires four strokes of its piston – two revolutions of the crankshaft - to complete the sequence of these 4 events
    - 1st revolution = intake (descend of the piston) + compression (rise of the piston)
    - 2nd revolution = expansion (descent of the piston) + exhaust (rise of the piston)
  - use of a valve timing system is mandatory ($\omega_{CAMSHAFT} = 0.5 \cdot \omega_{CRANKSHAFT}$)

Operating principle **2-stroke**

- **2-stroke cycle** (invented D. Clark 1878)
  - operating with 1 only crankshaft revolution (intake + exhaust in 1 motion)
    - compression stroke ⇒ when the piston rises
    - combustion & expansion ⇒ when the piston descends
  - the renewal of fresh charge is only feasible close to the BDC
    - whenever ports are uncovered, compressed fresh mixture (below: in the crankcase) flows into the cylinder and the scavenging process sweeps out the burnt gases

In theory, 2-stroke power = twice 4-stroke power.
In reality, power increase is only +30%, due to :
(i) the reduced effective expansion (=precompression) stroke and
(ii) increased heating due to the increased number of power strokes which limits the maximum speed (overheating).
This requires greater cooling and lubricating oil.
In a 4-stroke, for every 2^{nd} revolution the cylinder has time to cool.

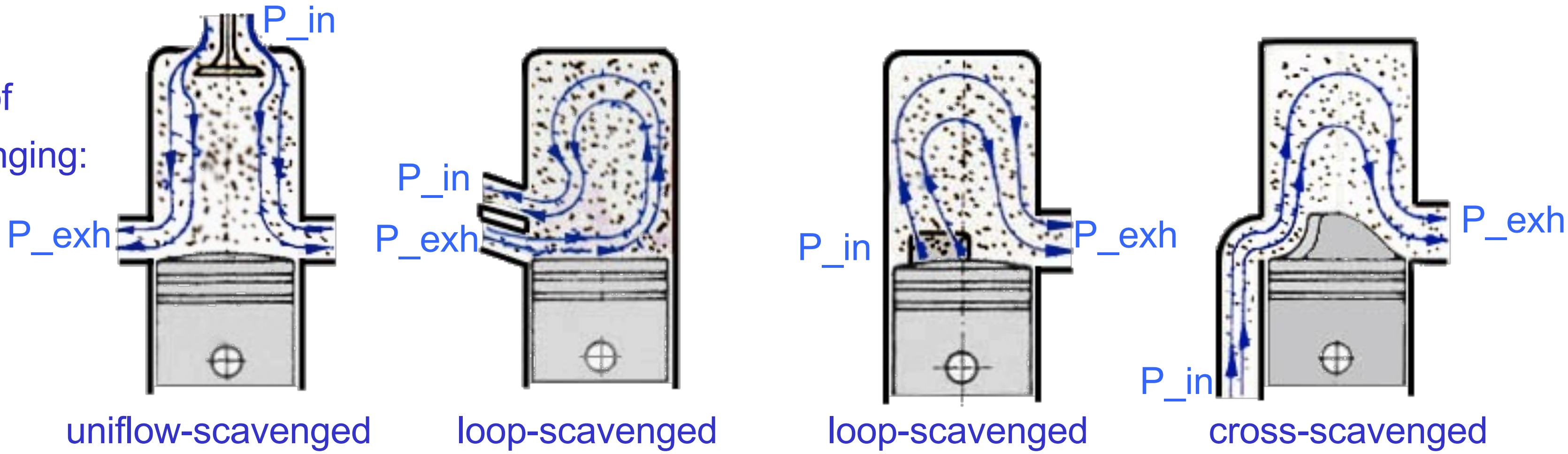


- mandatory condition for operation: $P_{INTAKE} > P_{EXHAUST}$

Operating principle **2-stroke**

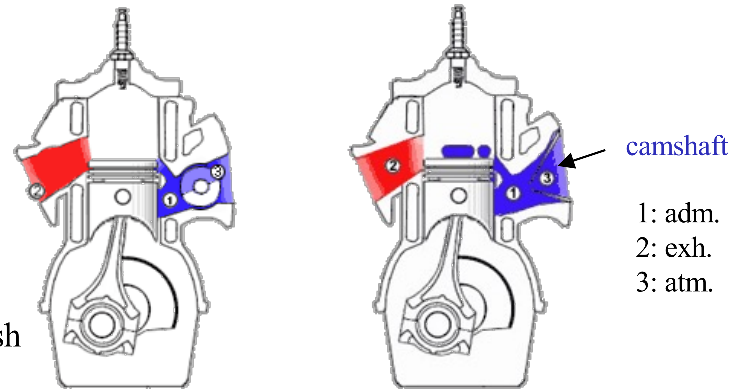
- 2-stroke cycle
  - requires a scavenging process in order to transfer the fresh mixture from the intake to the exhaust port, minimizing the losses:

Type of scavenging:



$$P_{INTAKE} > P_{EXHAUST}$$

  - possibility to use reed*-valve to avoid:
    - the discharge of burnt gases into intake ports
    - to loose fresh fuel charge into the crankcase



*overpressure-release, anti-backflush

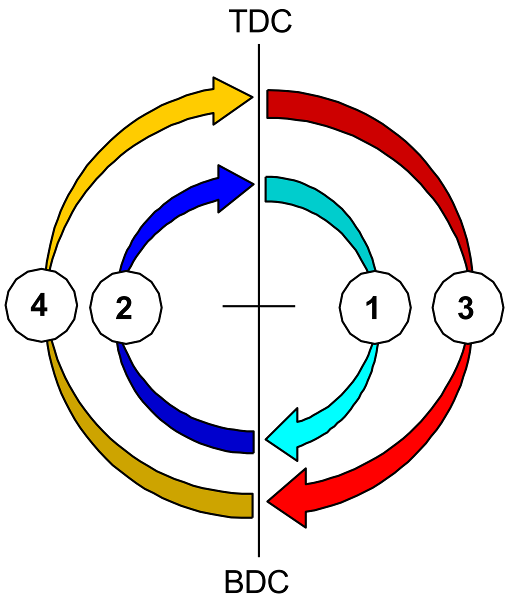
2-stroke : higher power from a same size engine, hence more compact.
No valves + valve actuation, hence mechanically simpler, cheaper and easier maintenance.
Torque on crankshaft also more uniform.

Operating principle : summary

- Summary: cycle of reciprocating engines

4-Stroke: $-360° < \varphi < +360$

2-Stroke: $-180° < \varphi < +180$



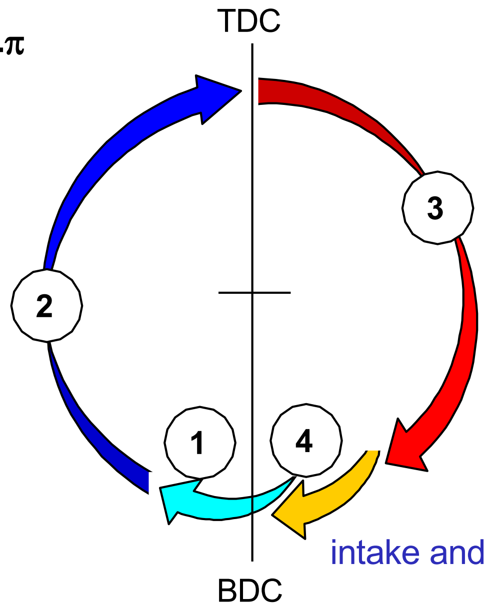
4-Stroke cycle : 4π

1 : Intake

2 : Compression

3 : Expansion

4 : Exhaust



2-Stroke cycle : 2π

1 : Intake - Scavenging

2 : Compression

3 : Expansion

4 : Exhaust

intake and exhaust close together

- : Lower specific power (1 power stroke per 2 revolutions)
(only 1 combustion every 2 revolutions)

+ : Driveability ↗ , Reliability ↗, Emissions ↘

Trade-off between gases evacuation
and losses of fresh mixture in exhaust pipe

- : Emissions ↗, Operating range ↘

+ : Specific power ↗ (1 power stroke per 1 revolution)

Comparison overview 4-stroke / 2-stroke

	4-stroke	2-stroke
Torque	Less uniform. Heavier flywheel	More uniform. Lighter flywheel
Engine size/weight	Heavier (only 1 power stroke per 2 revolutions)	Lighter, more compact, for the same power
Cooling need, wear, Lubrication need	Less	More
Intake	Valves + actuators	Ports
Cost	Higher (weight, valve system)	Lower
Volumetric efficiency	Higher (exhaust stroke revolution)	Lower (less time for intake)
Thermal efficiency	Higher (more time to cool)	Lower (higher avg. T, thus less ΔT)
Part load efficiency	Higher	Lower
Uses	Cars, trucks, buses, tractors, power generation (efficiency is important)	Scooters, (motorcycles), large ships (cost, weight, compactness are important)

Operating principle - **flows**

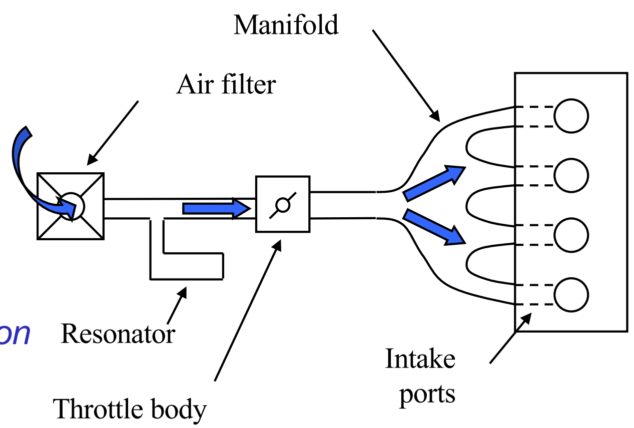
- (5) Flows inside reciprocating engines:

  1) Intake circuit ⇒ AIR
  2) Fuel circuit ⇒ GASEOUS *or* LIQUID FUEL
     (or both: dual fuel engine: gasoline + NG)
  3) Exhaust circuit ⇒ COMBUSTION GASES
  4) Lubrication circuit ⇒ OIL
  5) Cooling circuit ⇒ WATER (internal) *and* AIR (external)

Operating principle - flows

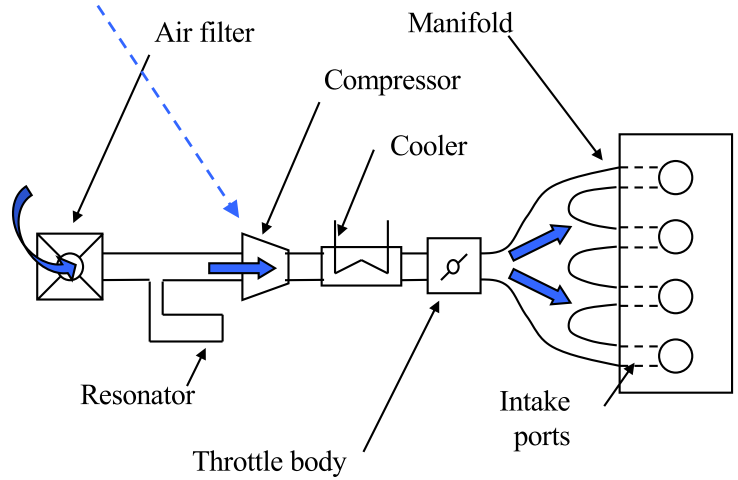
1) Intake circuit

- air induction ensured by intake ports
- more and more coupled to a supercharged system (1 or 2 stages)



for noise reduction

S.I.E.

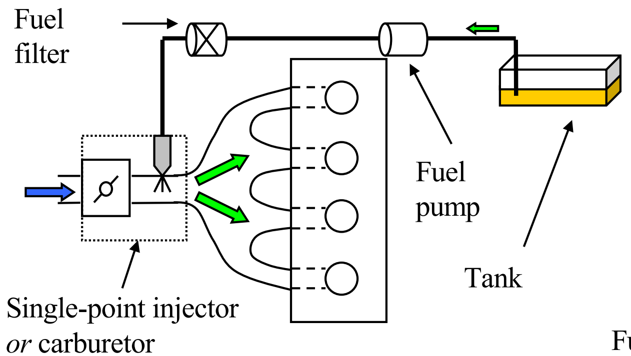


C.I.E.

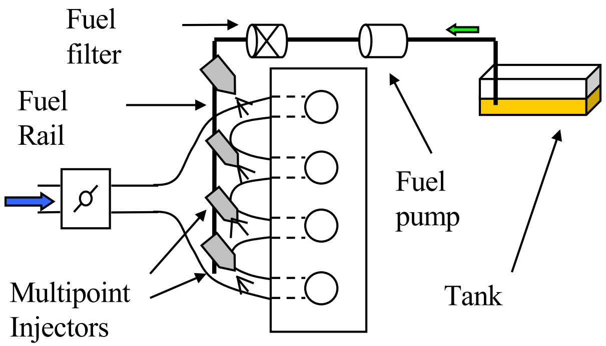
Operating principle - flows

2) <u>Fuel circuit</u>

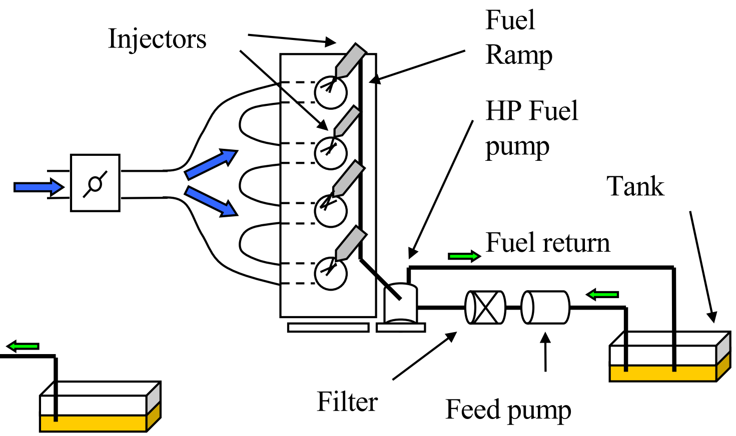
- intake of Air-Fuel mixture (Otto)
  ⇒ <u>indirect</u> injection (w.r.t. the comb. chamber) IN the intake system (5-100 bar)
- or only air intake into the cylinder (Diesel)
  ⇒ Fuel is <u>directly</u> injected INTO the combustion chamber (1000-2000 bar)



Single point indirect-injection



Multipoint Indirect-injection



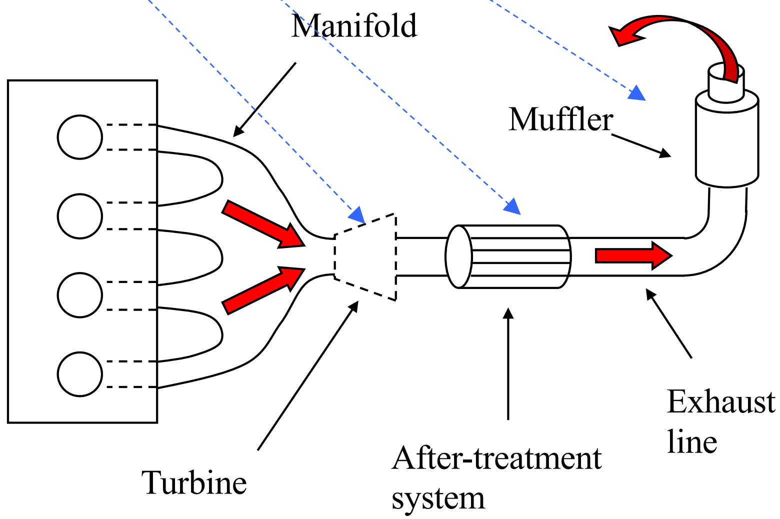
Direct-injection into the cylinder

Operating principle - flows

3) Exhaust circuit

In general, it contains:

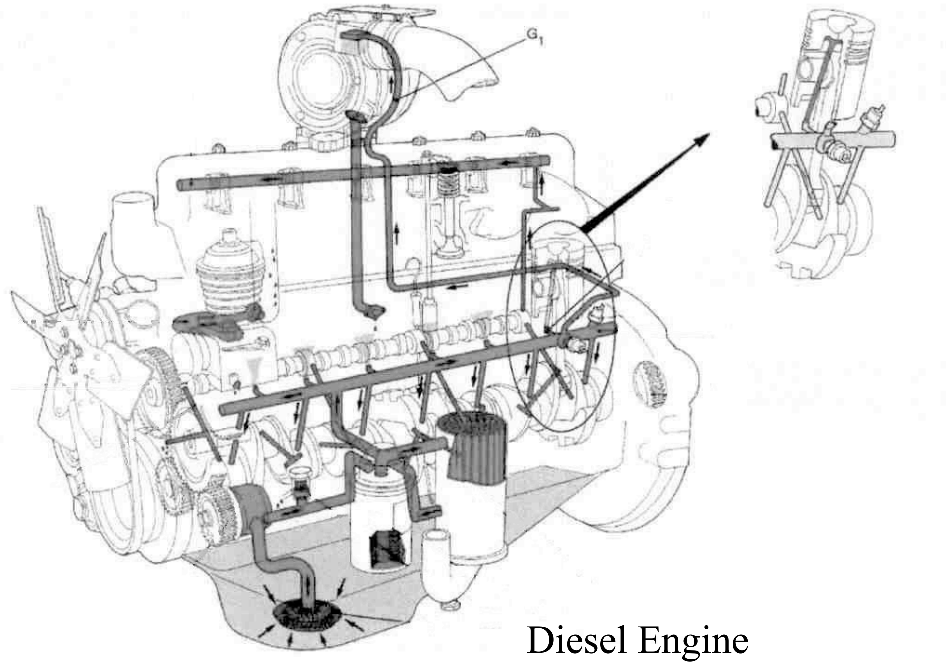
- noise reduction system (↘ dB)
- exhaust gas treatment system!
- turbocharged system (turbine)
  - to drive the intake compressor



Operating principle - flows

4) Lubrication circuit

- Oil tank *or* crankcase
- Feed pump
- Discharge valve (overpressure relief)
- Internal oil circuit
- External pipes
- Oil filter
- Heat-exchanger (oil-water)



Diesel Engine

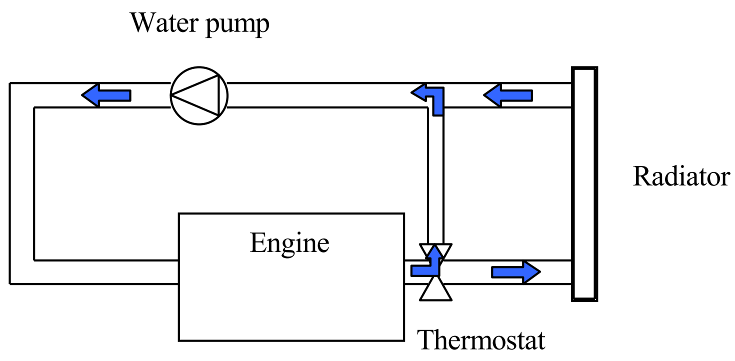
3D movie contd., with circuit flows

Operating principle - flows

5a) Internal cooling circuit ⇒ WATER

- water + additives: anti-corrosion & antifreeze (glycol)
- tank outside of the engine
- water pump
- water circuit (internal)
- thermostat (temperature control)
- external exchanger (heat evacuation)

  ⇒ air-water *or* water-water



5b) External cooling circuit ⇒ AIR

- suppression of “water circuit” components
- heat release ensured by:
  1. cooling fins located on the cylinder head and cylinder block
  2. air circulation outside to the engine

⇒ use the reserve for *on-board* application (airplane, motorcycles, scooters)

Content Chapter 1

- Introduction
- Description of the main components
- Operating principle
  - Mechanics of the reciprocating engine
  - Engine Cycles
  - Flows inside reciprocating engines
- **Classification**
  - Reciprocating Engines Families
  - Kinematics of the piston

Classification Reciprocating Engines Families

1) Thermodynamic cycle
   - 2-stroke cycle / 4-stroke cycle
2) Method of ignition
   - Spark ignition: OTTO *or* SI Engine (Spark Ignition)
   - Compression ignition: DIESEL *or* CI Engine (Compression Ignition)
   - Stratified charge ignition *or* SC Engine (Stratified Charge), FSI (fuel stratified injection), GDI (gasoline direct injection),…
   - Pilot injection ignition (of fuel oil *or* Diesel): Dual-Fuel
3) Type of fuel*
   - gasoline (petrol), fuel oil (Diesel fuel), natural gas, LPG, heavy fuel…
   - specials fuels: alcohols (methanol, ethanol), vegetable oil, H_2, …
4) Method of mixture-preparation / Injection system (p. 39)
   - Carburetor : mono *or* multi-body
   - Injection : single *or* multipoint, indirect / direct injection
   - High pressure injection system: Common rail, unit-pump, injection pump

*Type of fuel:

1. Volatile liquids (gasoline, alcohole, kerosene): homogeneous mixture with air, SIE
2. Gaseous (NG, LPG, biogas): mixed with air, SIE, more reduced ignition delay than liquids (=better)
3. Viscous, heavy, low volatility liquids : atomised droplets from fuel injector, CIE

Classification

- Reciprocating Engines Families (ctd.)

5) Air Induction
   - naturally aspirated engines: atmospheric
   - supercharged engines: turbocharger, turbocompounding, compressor…

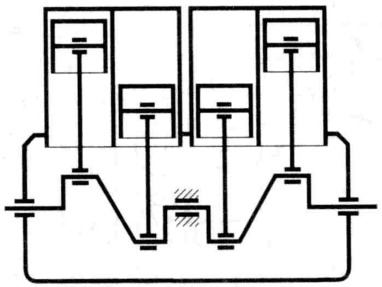
6) Method of cooling
   - air cooled, water cooled

7) Method of lubrication
   - oil crankcase / dry-sump oil system (“dry” crankcase)

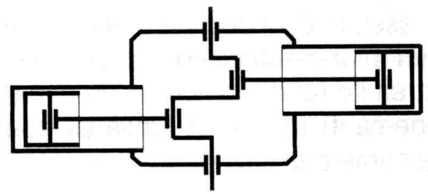
8) Basic geometrical design
   - Cylinder number: single-cylinder, multicylinder
   - Cylinder arrangement: L, V, B, W, X, U, O (p. 46)
   - valve train design: number of valves
camshaft design and location (OHC, DOHC,..)

Classification

- Cylinders arrangement (*or* type of design)

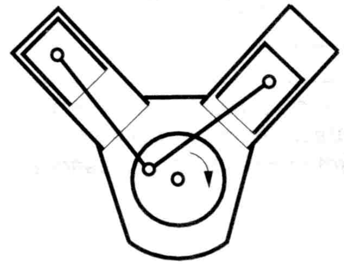


In-line : L (cars)

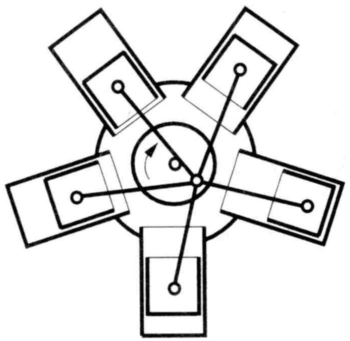


Flat opposed cylinder (Boxer) : B

(saves on height)

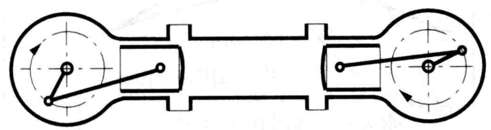


V (lower gravity point)



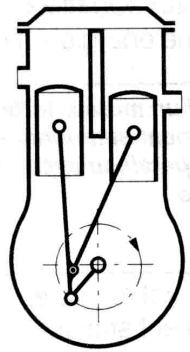
Radial: X

(air cooling)



Flat opposed-piston : O

(2-stroke, large engines)

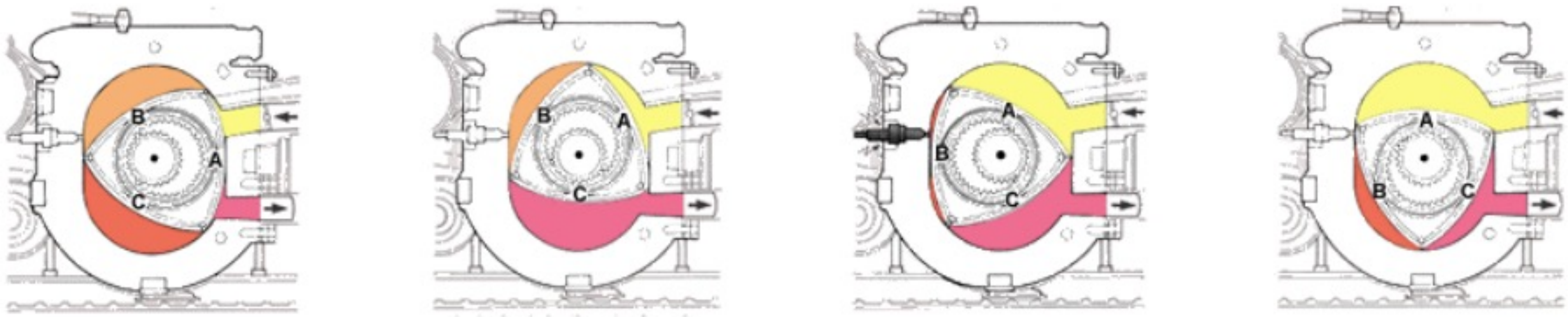


U

Classification

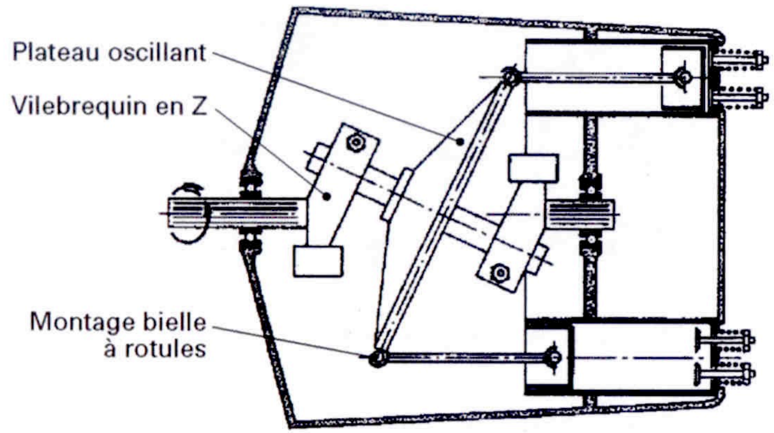
- Kinematics of the piston
  - until now ⇒ reciprocating engine

    But, don't forget...
  - **Rotary engines** (f.ex.: Wankel): only one component is in motion!



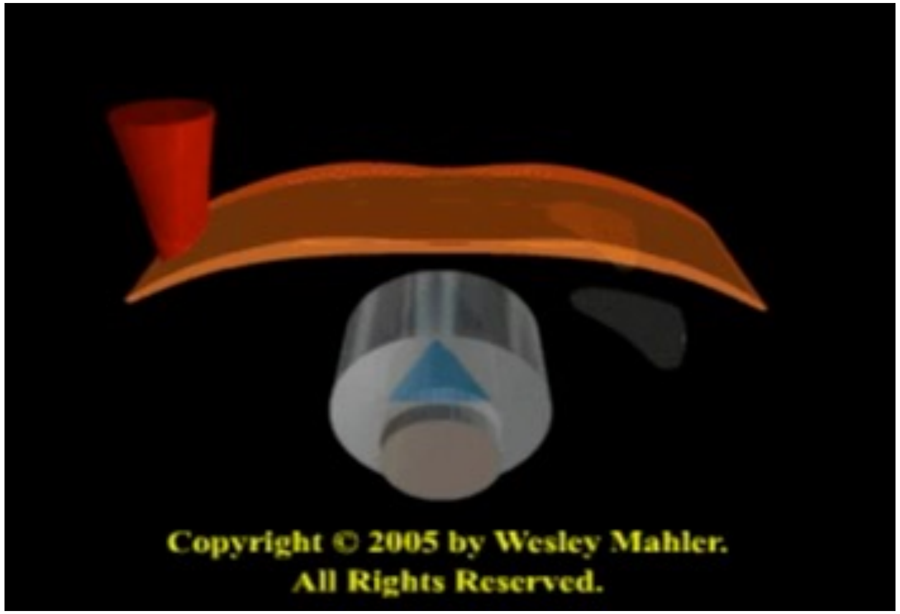
  - **Drum engine**

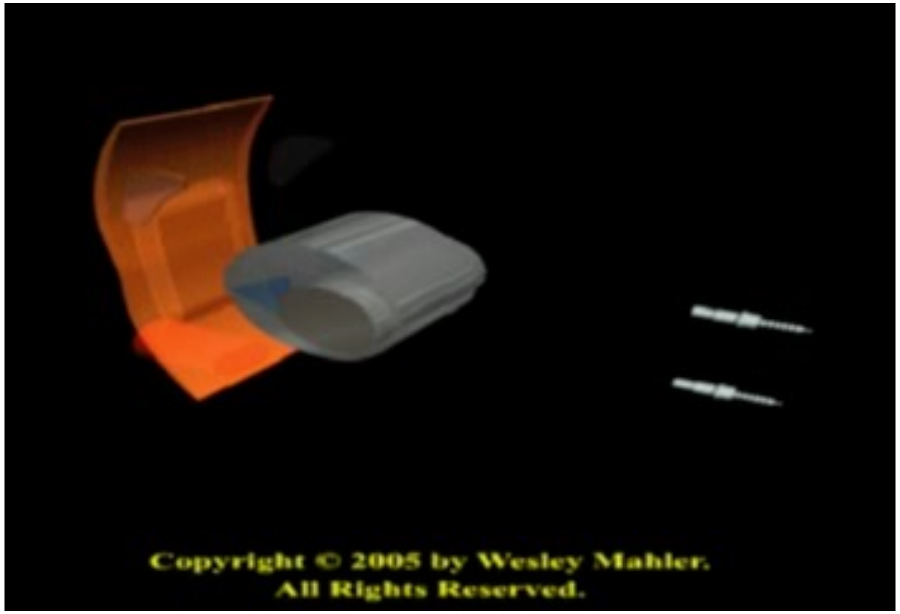
    or axial engine:



Classification

Wankel engine (Mazda)





Applications – some numbers

	2-stroke SI	2-stroke CI	4-stroke SI gasoline	4-stroke CI diesel
Dvpmt drivers	Simplicity, cost	High power	Efficiency, emissions, speed	Emissions, efficiency
Vehicles	50cc lawn mowers 100cc **scooters** (5 kW, 5500 rpm) 250cc motos (10 kW, 5000 rpm) Outboard boats	**Ship** propulsion 400-900 mm bore Up to 37 MW e.g. 800 mm bore, 1550mm stroke, 20 MW, 120 rpm	**Cars** 30-60 kW 4500rpm High power motos Small aircraft 400-4000 kW, e.g. 18-cylinder 2 MW	Small: pump sets, compressors, drilling rigs. Tractors: 50 kW **Jeeps, Buses, Trucks**: 40-100 kW Construction machines: 200-400 kW **Trains**: 600 kW – 4 MW **Marine**: 100kW – 35MW Stationary power
Characteristics	High fuel consumption (fuel scavenging loss, high speed)	Low speed, directly coupled to ship propeller, no gear		Versatility: 50-1000 mm 100-4500 rpm 1 kW-35 MW >100 kW: supercharged Vibrations High emissions

Design & performance data

Brake mean effective pressure *Brake specific fuel consumption*

Type	Size	Strokes	Com-pression Ratio	Bore (mm)	Stroke/ bore	Max speed (rpm)	Max bmep (bar)	Weight/ power kg/kW	Best bsfc (g/kWh)
Spark-ignition	small	2 / 4	6-10	50-85	0.9-1.2	4500-7500	4-10	2.5-5.5	350
	cars	4	8-10	70-100	0.9-1.1	4500-6500	7-10	2-4	270
	trucks	4	7-9	90-130	0.7-1.2	3600-5000	7	2.5-6.5	300
	Gas engines	2 / 4	8-12	220-450	1.1-1.4	300-900	7-12	23-35	200
	Wankel	4	9	0.57 L / chamber		6000-8000	10	0.9-1.6	300
Compression-ignition	Cars	4	16-20	75-100	0.9-1.2	4000-5000	5-7.5	2.5-5	250
	trucks	4	16-20	100-150	0.8-1.3	2100-4000	6-9	4-7	210
	trains	4 / 2	16-18	150-400	1.1-1.3	425-1800	7-23	6-18	190
	marine	2	10-12	400-1000	1.2-3.0	110-400	9-17	12-50	180

Consumption decreases with larger size, hence efficiency increases, due to reduced heat losses and reduced friction (lower speed)