Lecture 10: Engines

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- Work and cycles
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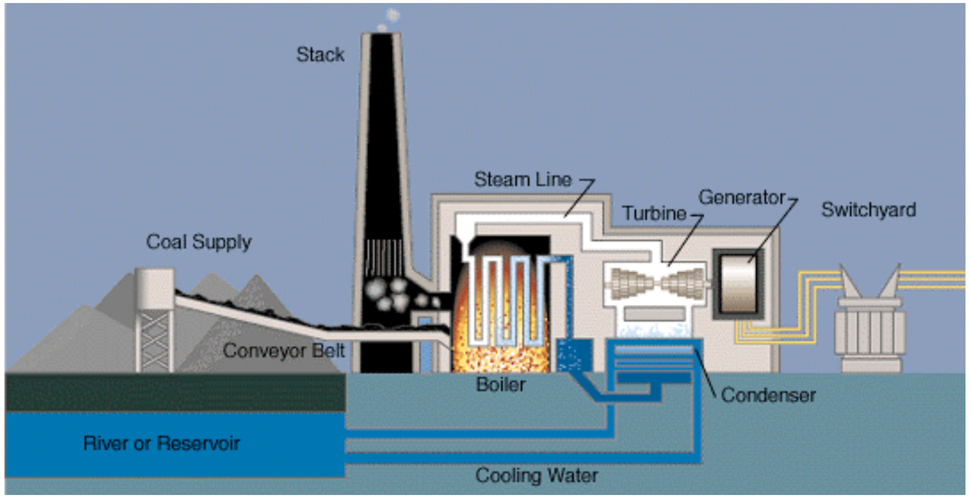
Reversibility revisited

	Work Out	Work Out (alt)	Work In	Net Work per Cycle
1 piece	0	$wx/2 - wx/2$	wx	$-wx$
2 pieces	$wx/4$	$wx/2 - wx/4$	$wx/4$	0
3 pieces	$wx/3$	$wx/2 - wx/6$	$wx/9$	$2/9 \times wx$
4 pieces	$3/8 \times wx$	$wx/2 - wx/8$	$wx/16$	$5/16 \times wx$
∞ pieces	$wx/2$	$wx/2 - 0$	0	$wx/2$
n pieces	$(n-1)/2n \times wx$	$wx/2 - wx/2n$	wx/n^2	$(n+1)(n-2)/2n^2 \times wx$

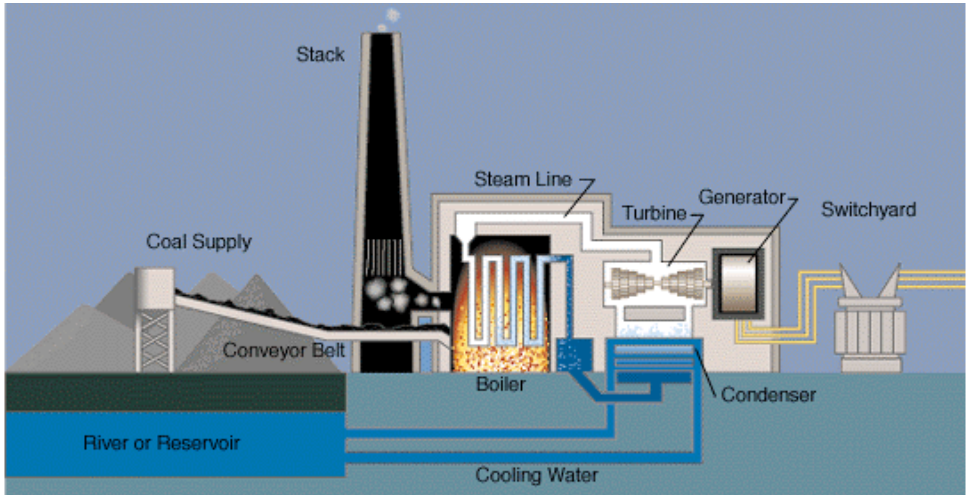
Introduction

- **Definition:** **A heat engine is a device that takes in energy as heat and, operating in a cyclic process (usually in *P* and *V*), expels some fraction of that energy as useful work, with the remaining energy passed out of the system as heat.**



A good example is the steam turbine that produces your household electricity. You burn coal, which produces input heat (good) plus CO_2 (not so good). The heat boils water creating steam at high pressure. This pressurised steam drives a turbine, which turns a generator (an electric motor run backwards) thereby producing useful work – an electric current through a resistive load (e.g, your appliances). There is also some heat loss (i.e., output heat) both in the hot CO_2 exhaust and from the steam turbine circuit to the surroundings via conduction, convection and radiation.

Introduction



A key thing to note is that only part of the energy absorbed as heat by the engine can be converted into useful work, and often this is quite low! We will see in the coming lectures that there is a limit to the useful work you can get out of a heat engine, which is set by the Second law of Thermodynamics. The highest work out to heat input ratio (called the efficiency as we'll see below) is produced by something known as the Carnot engine or Carnot cycle, which we'll discuss next week.

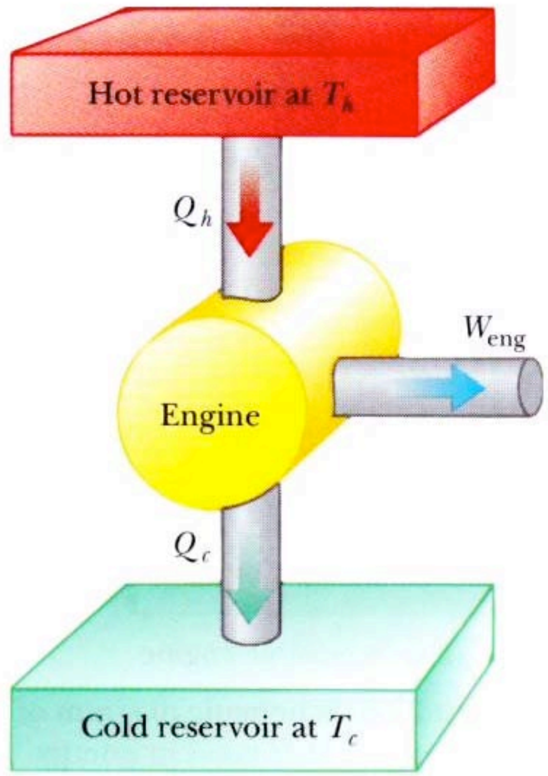
A generalised heat engine

- Heat engines come in many different forms, each with its own unique operating principle, (P,V,T) cycle, efficiency, advantages & disadvantages which are separate to, and often more important than, the efficiency alone.

- We hate such specific things in physics, what we like more are generalised versions that we can understand from a pure point of view and then adapt to specific cases as we need them.

- So what does a generalised heat engine look like? We have a hot reservoir at temperature T_h and a cold reservoir at temperature T_c, both connected to the 'engine'.

- In thermodynamics, a 'reservoir' is large enough that its temperature doesn't change noticeably when heat enters or leaves (equivalent to a ground or a constant potential in electronics).



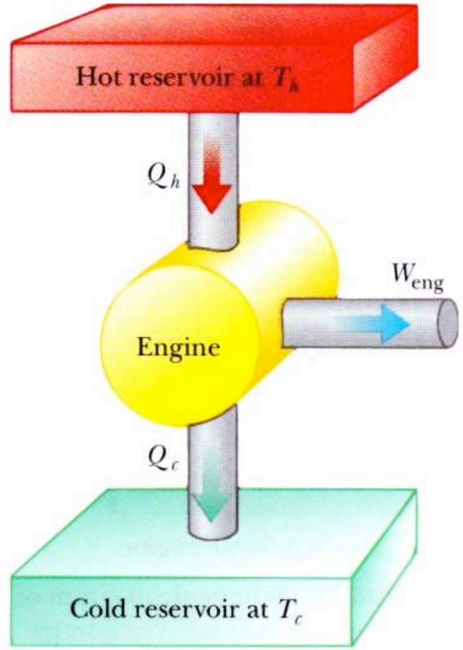
A generalised heat engine

- An amount of heat Q_h flows from the hot reservoir into the engine. Some of this heat is converted into work W, and the remainder Q_c flows as heat into the cold reservoir.

- By conservation of energy (i.e., the first law), we can immediately say that:

$$Q_h = W + Q_c \tag{10.1}$$

- Something to note is that there is nothing stopping us from feeding some of the waste heat Q_c back into the engine, but unless we keep supplying additional heat we will eventually run out of energy to keep providing useful work W.



- But, you can't just short the hot and cold reservoirs together, otherwise $T_h = T_c$ and the engine stops working.

- You can also 'add' and 'subtract' engines operating between the same two reservoirs – we will see more of this next lecture.

Work and cycles

- **The work *W* can come in many forms but mostly it comes as compressive work $dW = -PdV$. The work in any *PV* process is given by the area under the corresponding *PV*-curve, and for a closed *PV*-cycle the work done is the area inside the cycle.**

- **Why are cycles so important compared to just a simple *PV* process operated once or even repeated?**

- **Because a single process gives us one amount of work W_1. Suppose we want more work, if we go back to the beginning (i.e., reverse the process) then we have to put W_1 back in, and so in net we get no work at all.**

- **In contrast, if we have a cycle we get some net work out W_2, it might be more or less than W_1, but each time we repeat the cycle we get W_2 out, and this is really useful because if we repeat it enough (say *n* times) we will always get $nW_2 >> W_1$, and a continuous supply of work, very useful indeed.**

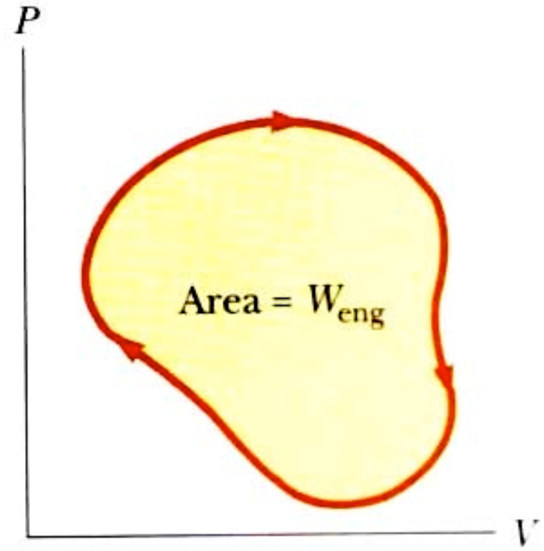


Figure 22.3 *PV* diagram for an arbitrary cyclic process taking place in an engine. The value of the net work done by the engine in one cycle equals the area enclosed by the curve.

Efficiency

- In order to decide how good a specific engine is, in a thermodynamic sense, we need to come up with some figure of merit, for example:

$$e = \frac{\text{benefit}}{\text{cost}} = \frac{W}{Q_h} \qquad \textbf{(10.2)}$$

The benefit we get from our generalised engine is the work *W* and the cost is the heat Q_h we put in to get that work, and we call *e* the efficiency. The more work we get out for a given heat in, the more efficient our engine is. If we combine Eqns 10.1 and 10.2, we can write:

$$e = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h} \qquad \textbf{(10.3)}$$

There are three things to note here:

- $Q_h \geq Q_c$ by definition and $Q_h, Q_c > 0$, so $0 \leq Q_c/Q_h \leq 1$, which means $0 \leq e \leq 1$, always.
- If $Q_h = Q_c$ (i.e., the heat goes straight through the engine giving no work), then $e = 0$.
- If $Q_c \rightarrow 0$ (i.e., the limit where all of Q_h gets converted into work), $e \rightarrow 1$.

Analysing an engine

- Suppose you are given an engine (we will do a worked example of this in a moment), a common thing to do is to go through and work out Q_h, Q_c, W and e. There is a general process to follow for doing this:

1. First and most obvious, you need to work out how the engine works. Where does the heat come from and go to, what form does the work take, etc.

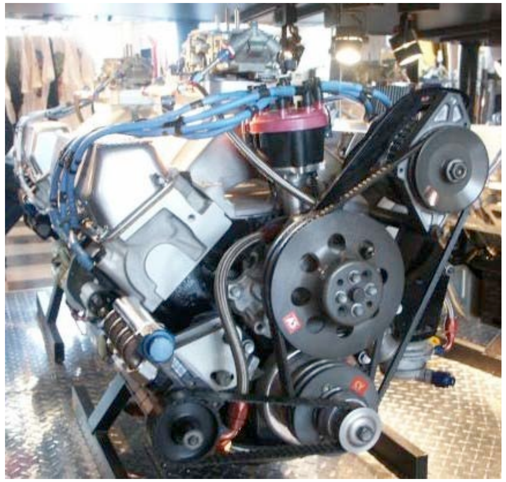
2. In most practical cases (but not always, so beware) the work will be compressive work and so what we're interested in is the engine's cycle in *PV*-space, so we need to work this out.

3. We can then analyse the *PV*-cycle, work out the heat flowing in Q_h, the heat flowing out Q_c and most importantly the work done W, which is the area inside the *PV*-cycle.

4. Finally, we can work out the efficiency e using Eqn 10-2 or 10-3.

Let me show you how to do this using an extremely common example, one of the most heavily developed and common heat engines in existence, the petrol-fueled internal combustion engine.

The internal combustion engine

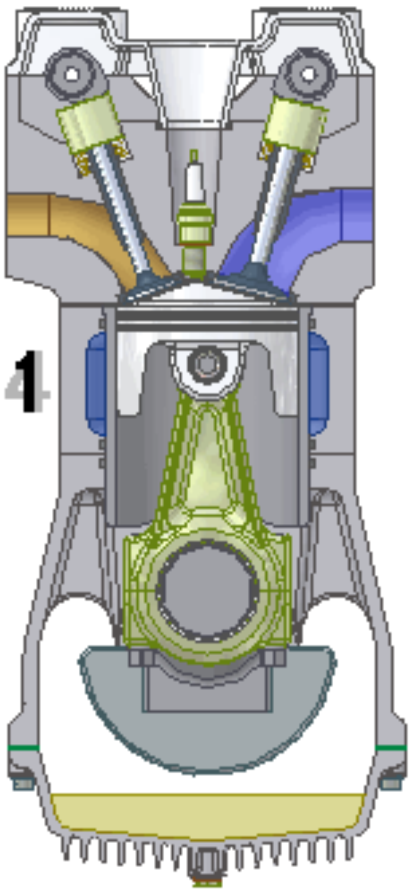


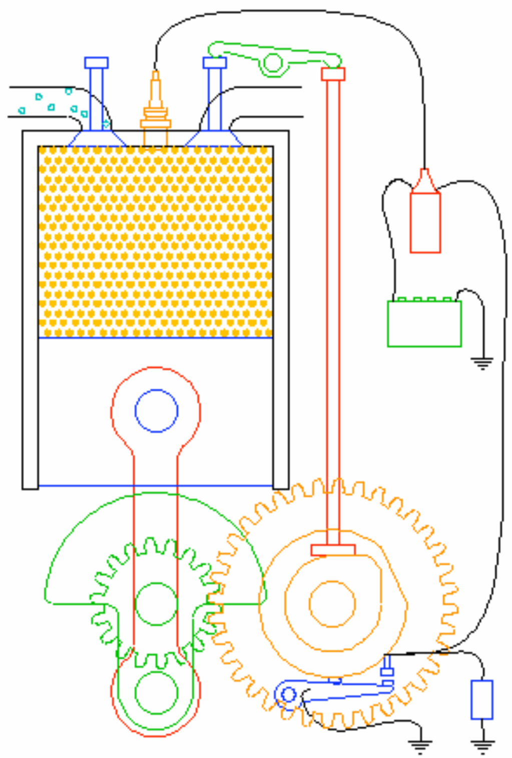
- **The vast majority of cars on the road are powered by a petrol-fuelled four-stroke internal combustion engine – there are slight variations in layout, number of cylinders, etc. but the basic operating principles are always the same.**

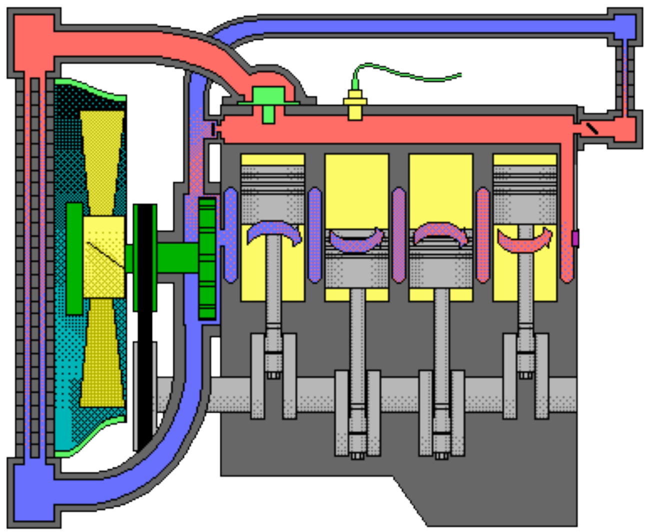
The four-stroke petrol engine is not quite universal though, many trucks, trains and buses run diesel engines (as do cars), some cars run more exotic engines such as the rotary engine (e.g., the Mazda RX-7), and some smaller motorbikes and scooters, lawnmowers, etc will run a two-stroke engine. Light aircraft with propellers will often run four-stroke engines, but many aircraft will run jet turbine engines, which operate very differently.

The four-stroke petrol engine

- **There are a lot of sub-systems in an engine but if we reduce our focus simply to the thermodynamic system that takes in heat and produces useful work, we find our familiar piston and cylinder again.**

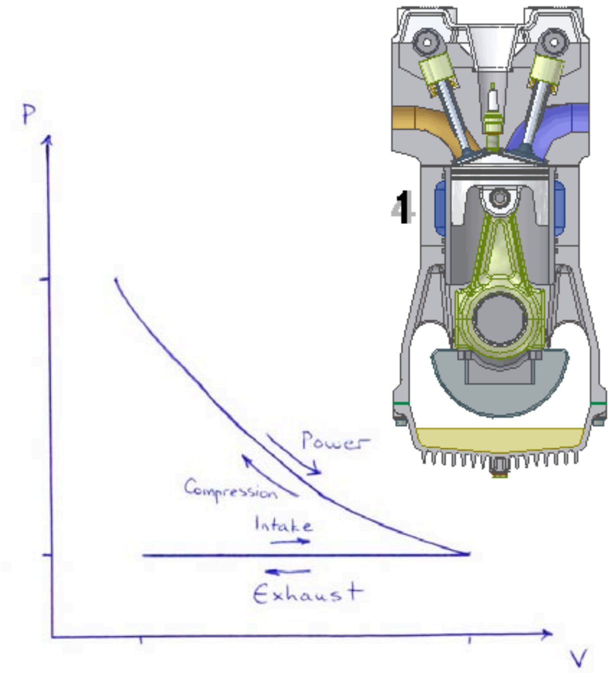






The Otto cycle

- The four-stroke engine is so-called because in each cycle, the piston makes four 'strokes' or up/down motions in the cylinder (i.e., it goes down, up, down, up). The four strokes are:



1. **Intake stroke:** The piston moves down increasing the cylinder volume. During this stroke, the inlet valve is open allowing fuel-air mixture into the cylinder. Because the system is open, this is a constant P process ~ 1 atm.

2. **Compression stroke:** The piston moves up with both valves closed, compressing the gas inside. This is a rapid adiabatic process (constant Q), resulting in a significant temperature increase in the gas.

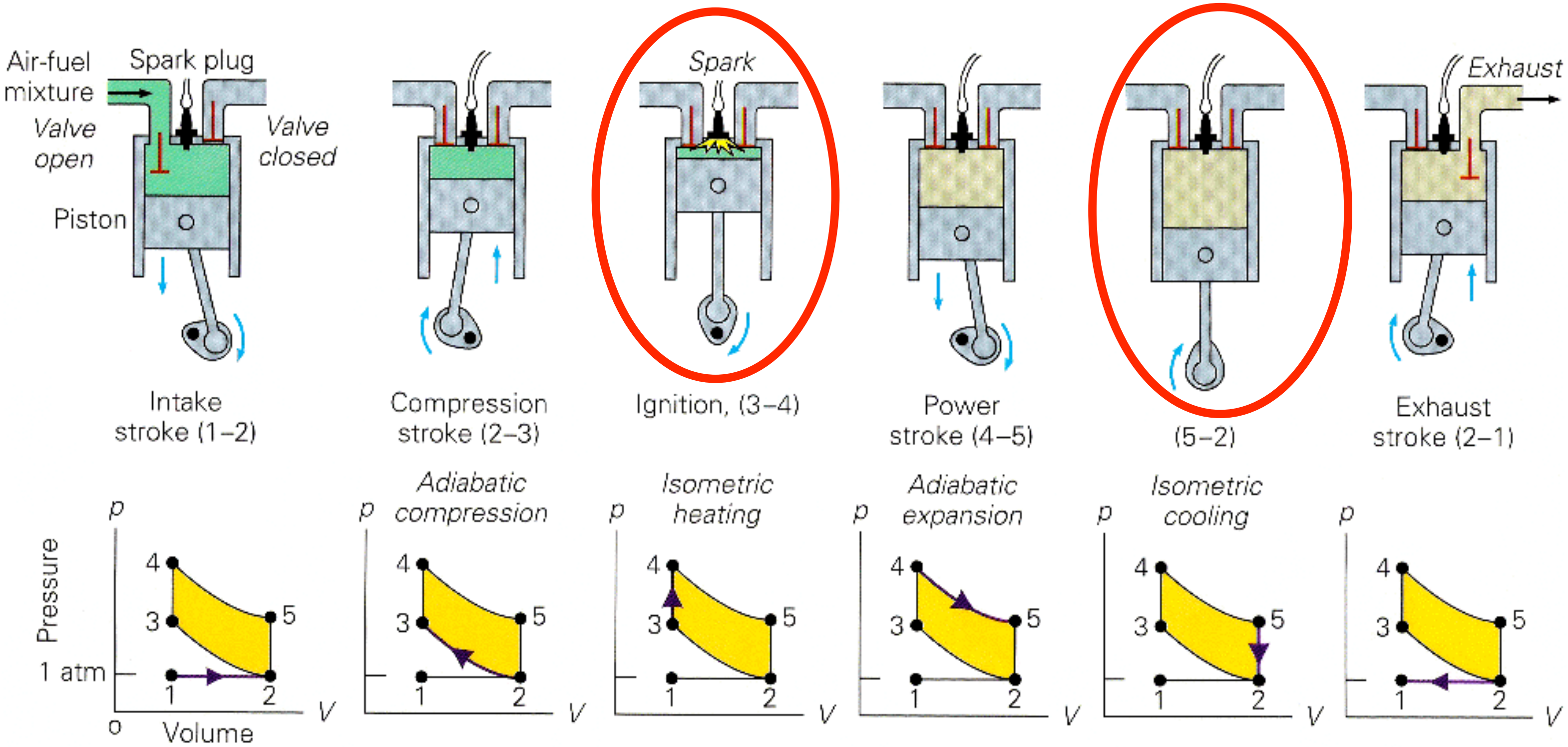
3. **Power stroke:** The piston moves back down with both valves closed, another adiabatic process, this time an expansion.

4. **Exhaust stroke:** The piston moves back up with the outlet valve open, pushing the exhaust gases or unburnt fuel-air mixture out of the chamber at constant P ~ 1 atm.

If we plot the *PV*-diagram, we get something that looks like that above. The cycle contains no area and produces no work – as we'd expect (if this isn't what you'd expect, go home, disconnect your spark plugs and try starting your car!).

The Otto cycle

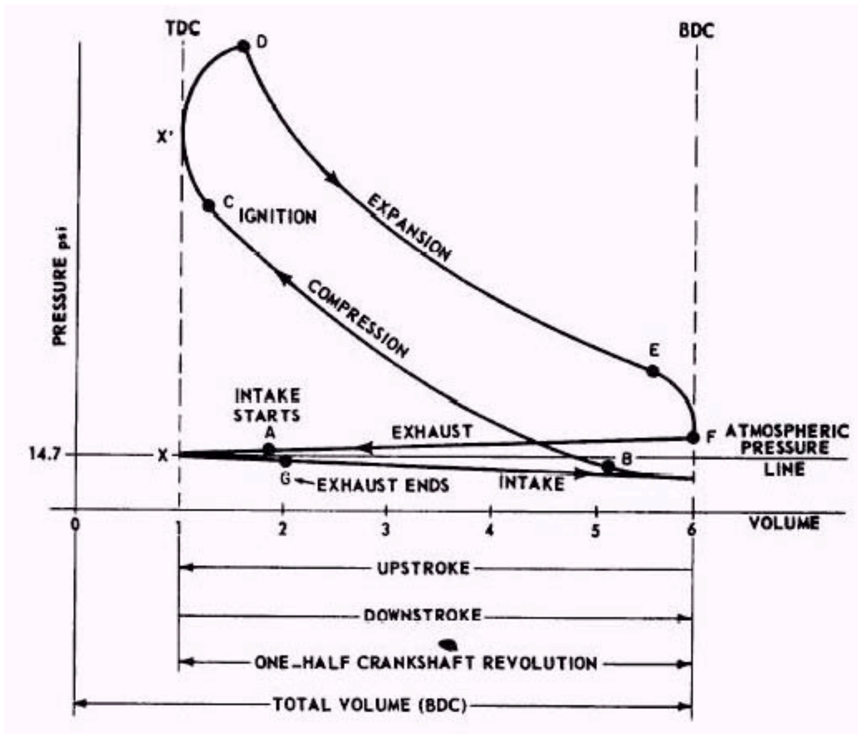
- **To get our engine to work, we need to add two extra components to our cycle (which still has four strokes) as shown below.**



The first is a combustion/ignition stage, which happens between the compression and power strokes – it's extremely fast and is thus a constant volume process. The second is a cooling stage, which happens between the power and exhaust strokes. This is also an extremely fast, constant volume process. Note that we now have an area inside our cycle and so we get useful work when the fuel-air mixture burns.

The real Otto cycle

- Some of you will be feeling a little dubious about how realistic this cycle is, particularly regarding the cooling step between the power and exhaust strokes, and you'd be quite right. A realistic Otto cycle is shown below.



It's not too dissimilar to the 'ideal' Otto cycle we've looked at so far. The differences actually reduce the efficiency, and so the ideal cycle is quite useful as it represents the most efficient possible case for an Otto cycle engine. We'll now calculate the efficiency of an ideal Otto cycle.

For the petrol-heads

For La Marseillaise, see:
http://www.youtube.com/watch?v=HSNAtKhzBKQ

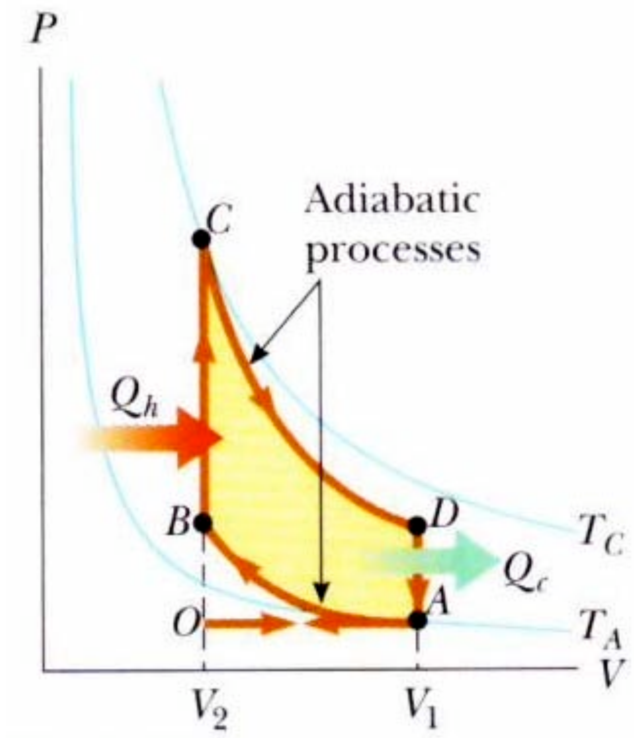
Calculating the efficiency of the Otto cycle

- **In the ideal Otto cycle, the intake-exhaust branch contains no area, and so as far as the work and efficiency is concerned, we can ignore it.**

This gives us a four-branch cycle A-B-C-D-A as shown below, which consists of an adiabatic compression during the compression stroke (A-B), a constant volume increase in pressure when the combustion occurs (B-C), an adiabatic expansion during the power stroke (C-D) and a constant volume decrease in pressure as the exhaust cools before the exhaust stroke (D-A).

Note that the heat Q_h comes in during combustion (B-C), and produces work *W* (given by the *PV*-area enclosed in the cycle) and some waste heat Q_c, which leaves the system during the cooling stage (D-A).

In our ideal cycle no heat enters or leaves the system during the compression (A-B) and power (C-D) strokes because these processes are adiabatic.



Calculating the efficiency of the Otto cycle

- **In this lecture I'll do the general case, and will let you do a numerical example as one of the tutorial problems.**

Firstly, we know that for a closed cycle Δ*U* = 0, so the first law gives Δ*U* = *Q* + *W* = Q_h – *W* – Q_c = 0 and hence:

$$W = Q_h - Q_c \qquad \textbf{(10.4)}$$

We could equally well just note Eqn 10-4 from conservation of energy and avoid the formal version of the first law entirely ☺. Considering processes B-C and D-A first, these are constant volume processes so we can write:

$$Q_h = nC_V(T_C - T_B) \qquad \textbf{and} \qquad Q_c = nC_V(T_D - T_A) \qquad \textbf{(10.5)}$$

Using these two expressions in Eqns 16-2 and 16-3, we can write:

$$e = \frac{W}{Q_h} = 1 - \frac{Q_c}{Q_h} = 1 - \frac{nC_V(T_D - T_A)}{nC_V(T_C - T_B)} = 1 - \frac{T_D - T_A}{T_C - T_B} \qquad \textbf{(10.6)}$$

Calculating the efficiency of the Otto cycle

Now let's consider the two adiabatic processes A-B and C-D, for which we can write $T_A V_A^{\gamma-1} = T_B V_B^{\gamma-1}$ and $T_C V_C^{\gamma-1} = T_D V_D^{\gamma-1}$. We also know from the *PV*-diagram that we can write $V_A = V_D = V_1$ and $V_B = V_C = V_2$. So here we can play a trick that goes something like:

$$T_A = T_B \left(\frac{V_2}{V_1}\right)^{\gamma-1} \quad \text{and} \quad T_D = T_C \left(\frac{V_2}{V_1}\right)^{\gamma-1} \qquad \textbf{(10.7)}$$

Subtracting these, we get:

$$T_D - T_A = T_C \left(\frac{V_2}{V_1}\right)^{\gamma-1} - T_B \left(\frac{V_2}{V_1}\right)^{\gamma-1} \quad \text{or} \quad \frac{T_D - T_A}{T_C - T_B} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} \qquad \textbf{(10.8)}$$

And if we put Eqn 10-8 back into 10-6, we get:

$$e = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma-1} \qquad \textbf{(10.9)}$$

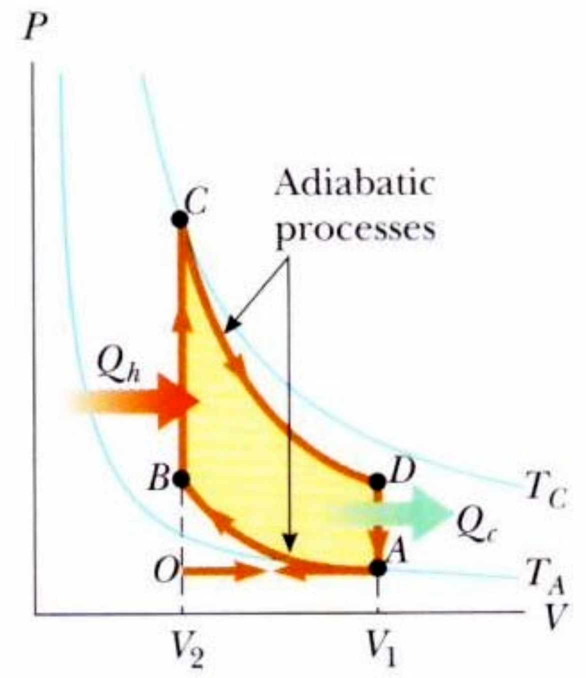
Calculating the efficiency of the Otto cycle

And if we put Eqn 10-8 back into 10-6, we get:

$$e = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma-1} \qquad \textbf{(10.9)}$$

The ratio of the two volumes V_2/V_1 is something known as the compression ratio r for the engine, but we can write this in terms of the temperatures also, because using Eqns 10-9 and 10-10 we know that:

$$\left(\frac{V_2}{V_1}\right)^{\gamma-1} = \frac{T_D}{T_C} = \frac{T_A}{T_B} \qquad \textbf{(10.7)}$$



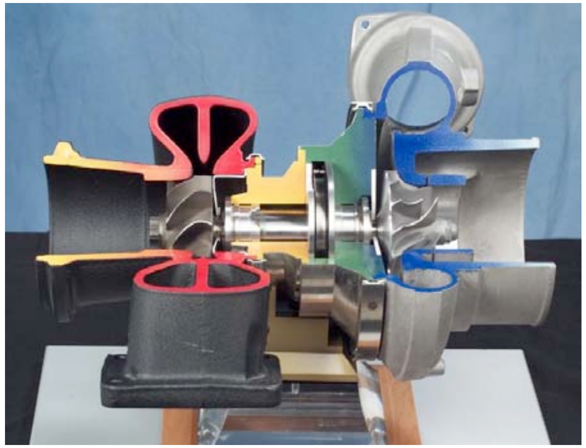
And so:

$$e = 1 - \frac{T_D}{T_C} = 1 - \frac{T_A}{T_B} \qquad \textbf{(10.8)}$$

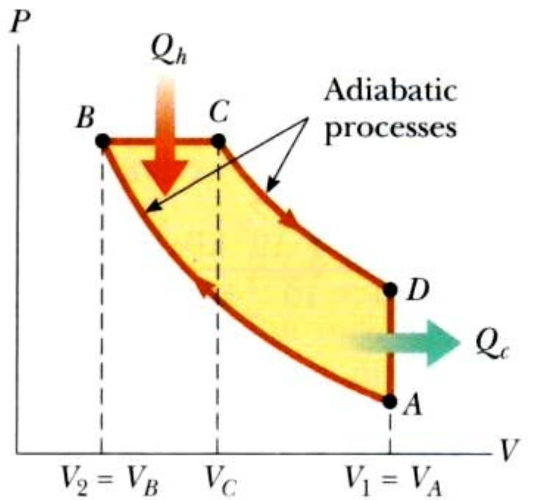
Some final observations

There are two common modifications made to engines, that are easy to make sense of, based on what we've learned so far.

1. **Turbo:** A turbo is used to increase the output power of an engine by increasing the pressure in the cylinder at the start of the compression stroke. This has two effects, it gives more work per cycle because $dW = -PdV$ and it means more fuel is in the cylinder when the spark is fired, increasing the heat input Q_h into the cycle. The turbo is a pump driven by the exhaust gases leaving the engine, in a sense this is recycling some of the waste heat Q_c.



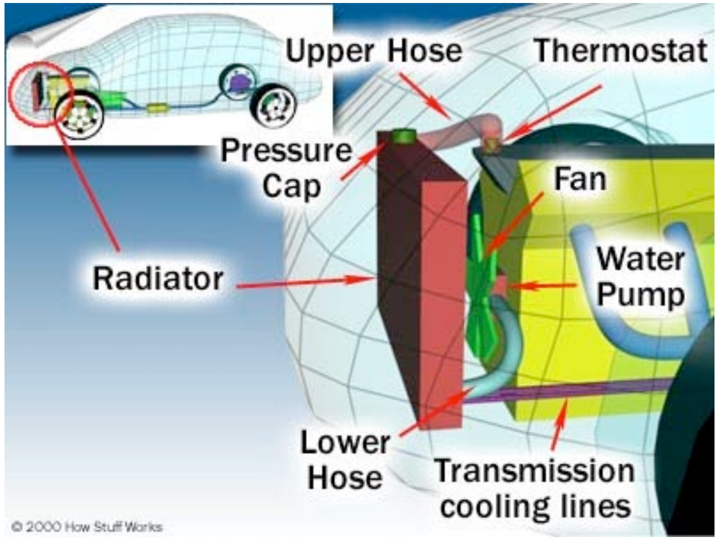
2. **The Diesel engine:** A diesel engine has no spark plug, and relies on the adiabatic compression to increase the temperature of the fuel-air mixture above its flashpoint (temperature at which it spontaneously combusts). This alters the cycle slightly, such that the combustion phase goes from being a constant volume process to being a constant pressure process.



Some final observations

As you'll see when you all do Question 1 in Tutorial 4, you can use this approach from a knowledge of a few engine parameters (displacement volume of the pistons, compression ratio and combustion temperature) to calculate the heat input/output, work done and net power of an engine with pretty good accuracy.

One final Observation - How do you cool your engine? Forced convection of course



Summary

- **A heat engine is a device that takes in energy as heat and, operating in a cyclic process (usually in P and V), expels some fraction of that energy as useful work, with the remaining energy passed out of the system as heat.**

- **The highest work out to heat input ratio, called the efficiency e, is produced by the Carnot engine or Carnot cycle.**

- **A generalised heat engine consists of a hot reservoir at a temperature T_h and a cold reservoir at a temperature T_c, both of which are connected to the 'engine'. An amount of heat Q_h flows from the hot reservoir into the engine. Some of this heat is converted into an amount of work W, and the remainder Q_c flows as heat from the engine into the cold reservoir.**

- **A generalised heat engine has an efficiency $e = W/Q_h = 1 – Q_c/Q_h$**

- **The four-stroke petrol internal combustion engine is one of the most common forms of heat engine in application today. It operates using a PV-cycle known as the Otto cycle with four stages consisting of an adiabatic compression, a constant volume heating, an adiabatic expansion and a constant volume cooling process.**

In the next lecture, we will look at the second law and its relationship to heat and work.