Lecture 7
April 19, 2011

Chapter III of RK

Heat Engines and thermodynamics

1st Law of Thermodynamics:
Heat and Work are on the same footing

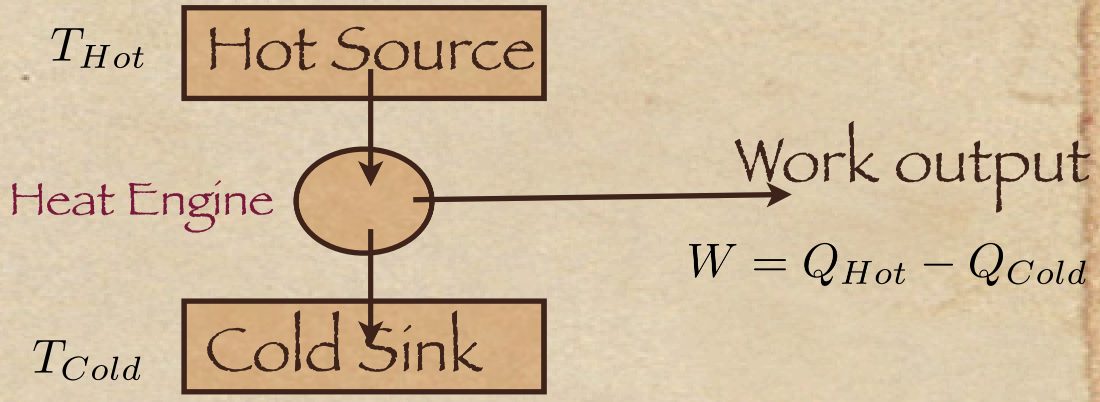
$$\Delta U = \Delta Q + \Delta W$$

We can convert work done to heat with great effectiveness: Think heated wire (Joule heating of resistors)

BUT: The matchstick example shows that converse is not so easy!

Converting heat into useful work is only possible in a "Lossy" fashion- we lose some heat to unwanted waste.

$$\text{Efficiency} = \frac{\text{Work done}}{\text{energy put into system}} \times 100\%$$



T_{Hot} Hot Source

Heat Engine

Work output

$W = Q_{Hot} - Q_{Cold}$

T_{Cold} Cold Sink

$$\text{Efficiency} = \frac{Q_{Hot} - Q_{Cold}}{Q_{Hot}} \times 100\%$$

$$\text{Efficiency(Carnot)} = \frac{T_{Hot} - T_{Cold}}{T_{Hot}} \times 100\%$$

Carnot showed that this is optimal.
(Cannot beat Carnot)

Summary: Carnot showed: Q(Cold) /Q(Hot) is at most T(Cold)/T(Hot)

In general Q is a complex object but T is simple (just measure it!). Hence this is a great simplification.

Examples:

Carnot's Car: T(Hot)= Burning temp of fuel, T(Cold)= atmospheric temp (1000-20)/1000 x 100 = 98%

Real cars ~25 to 30%

Coal fueled Power plant: T(Hot) = Coal temp, T(Cold)= river temperature;

Questions:
Why do we lose so much, is this preventable?
What, if anything, went wrong with 1st law of thermodynamics?
Is there a piece of the story that we haven't learnt yet?

Converting mechanical energy to
heat energy is easy, converse is difficult,
although allowed by 1st Law of thermodynamics

Efficiency definition and Carnot cycles emerge next.

2nd Law of thermodynamics

- It is impossible for a machine to take heat from a reservoir at T, produce work and exhaust heat into a reservoir at same T .
- Systems isolated from the environment will move towards equilibrium with their surroundings.

Linked ideas/concepts
Impossibility of perpetual motion.

Arrow of time:

Example: glass of water with ice in it will warm up in a room at normal temperatures: (e.g. 65°F) .

A Gas on one side of a chamber will fill both sides on removing partitions.

Other consequences:

* 1. Heat will not flow spontaneously from a cold object to a hot object.

* 2. Any system which is free of external influences becomes more disordered with time. This disorder can be expressed in terms of the quantity called entropy.

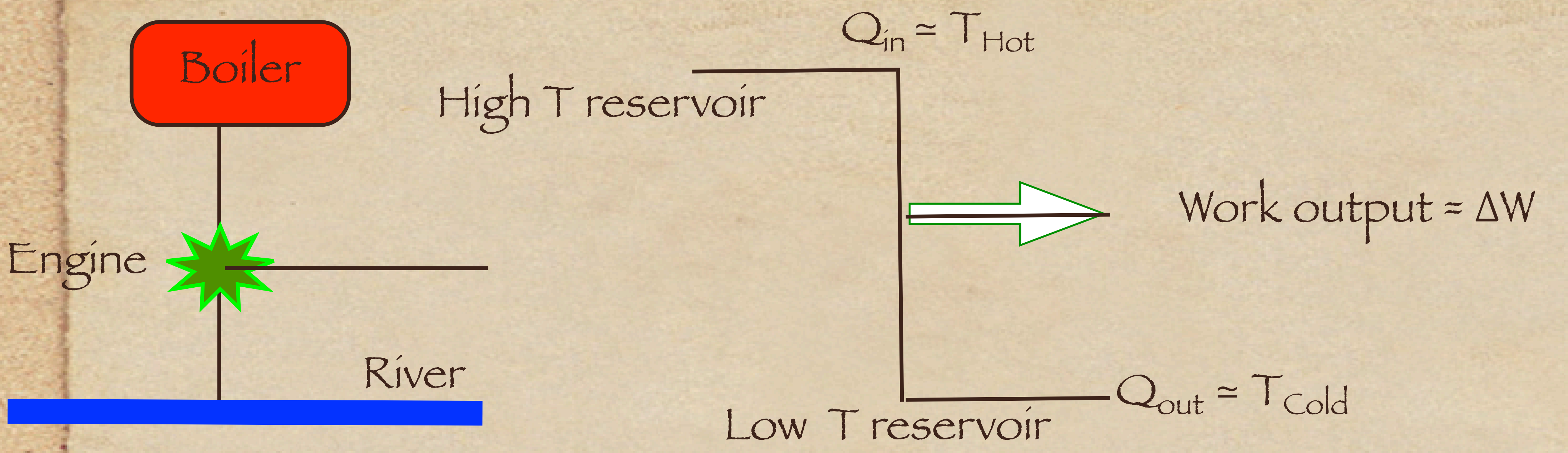
* 3. You cannot create a heat engine which extracts heat and converts it all to useful work.

* 4. There is a thermal bottleneck which constrains devices which convert stored energy to heat and then use the heat to accomplish work. For a given mechanical efficiency of the devices, a machine which includes the conversion to heat as one of the steps will be inherently less efficient than one which is purely mechanical.

COMMENTS

First law does not preclude this!

Entropy makes its grand entrance here. It is a measure of how disordered the system is. At T=0 Kelvin, entropy is zero since all motion ceases (Barring QM zero point motion)



High T reservoir

$Q_{in} \simeq T_{Hot}$

Work output $\simeq \Delta W$

Low T reservoir

$Q_{out} \simeq T_{Cold}$

First Law implies that

$$Q_{in} - Q_{out} \simeq \Delta W$$

Second Law says:
There is an intrinsic limit
on how good our engine can get

$$\eta \leq 100\%$$

$$\eta(Carnot) = \frac{T_{Hot} - T_{Cold}}{T_{Hot}} \times 100\%$$

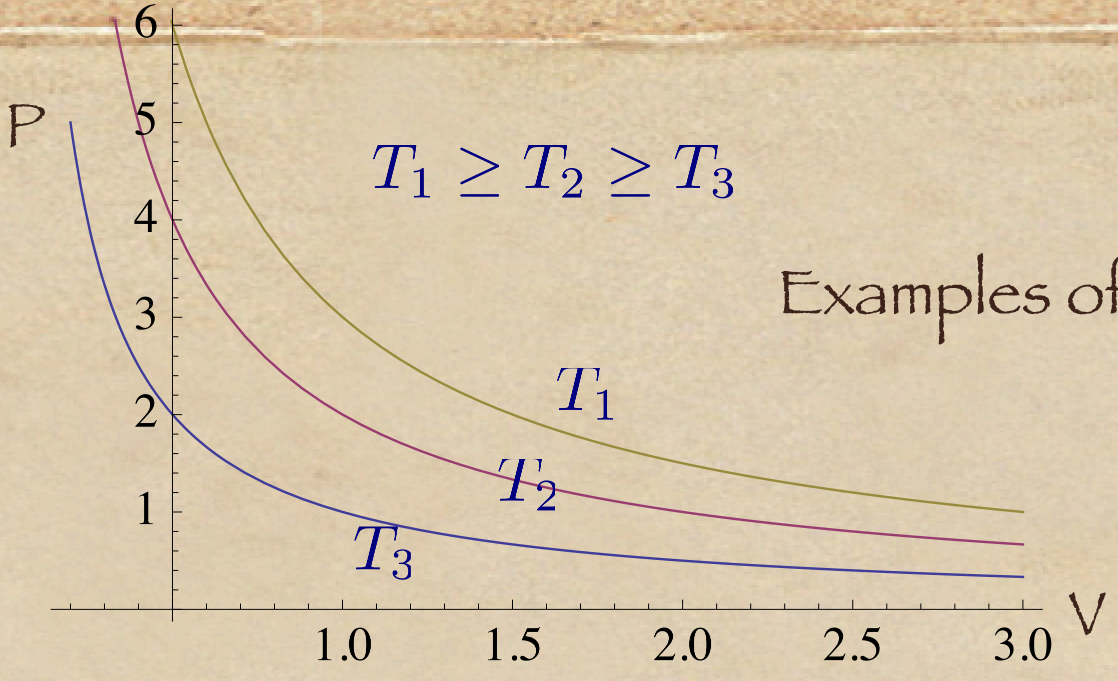
Carnot efficiency:

Key ideas to note:

- p V curves: ideal gases and fluids
- Work done as area of p V curve
- reversible processes versus irreversible processes
- isothermal processes
- adiabatic processes
- Cyclic process and work done in such a process
- Carnot's cycle and ideal engine
- Heat Pumps

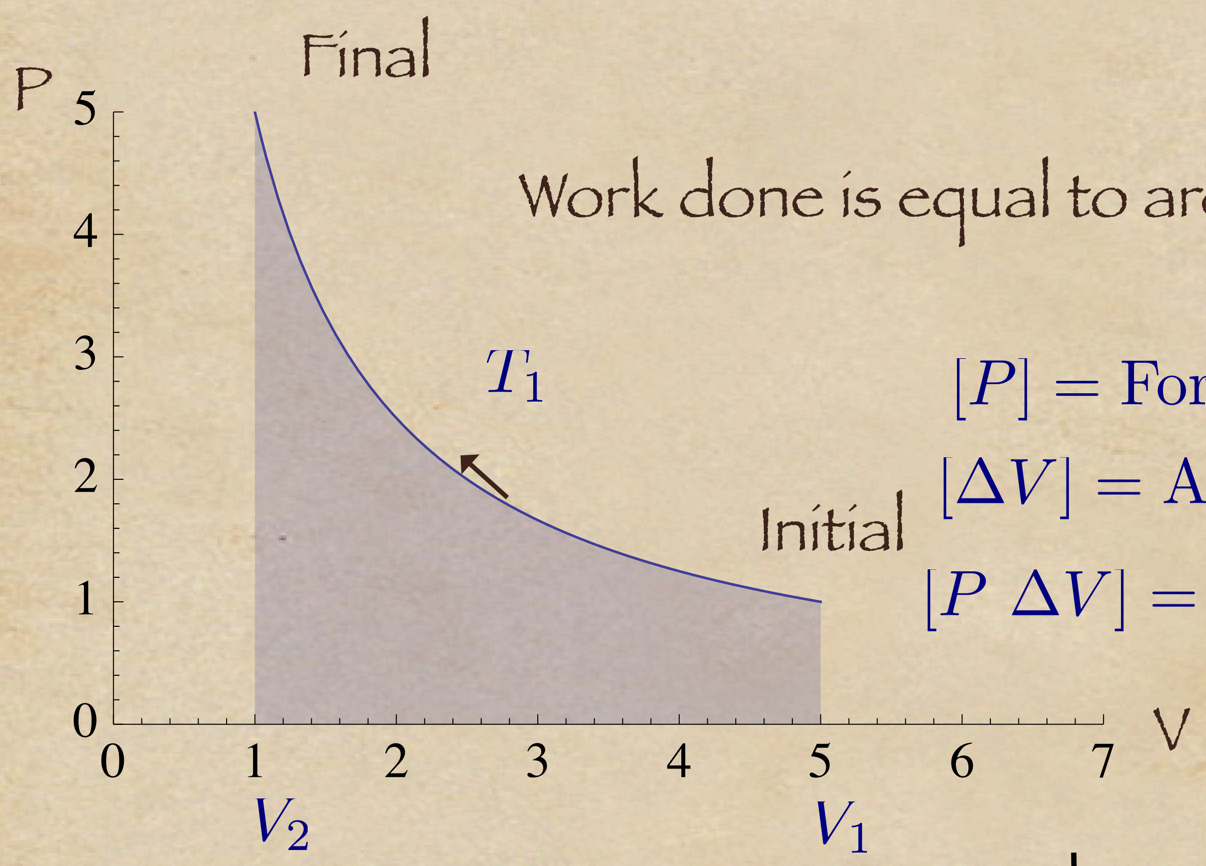
Ideal gas laws:

$$PV = nk_BT$$



Examples of Isotherms

Work done is equal to area under curve:



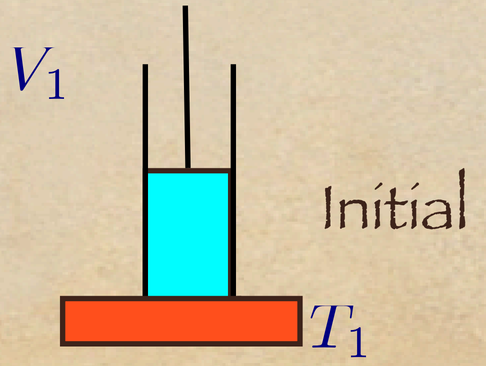
$[P] = \text{Force/Area}$

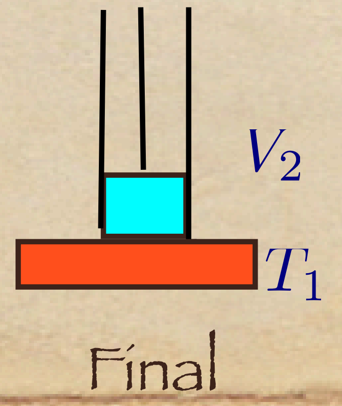
$[\Delta V] = \text{Area Length}$

$[P\ \Delta V] = \text{Force Length} = \text{Energy}$

$-P\Delta V = \text{Work done on fluid}$

$\Delta V = \text{Volume change}$





Irreversible versus reversible changes

Reversible and Irreversible processes:

Mechanical processes:	Thermodynamic processes:
Reversible processes examples • Projectile with no air resistance (e.g. on moon) • Particle slides without friction on a very smooth table top, e.g. hockey puck on ice. • Newton's laws: e.g. planetary motion • Schrodinger equation in QM.	**Reversible processes examples** • Slow compression so that at any point one is very close to equilibrium. • Slow expansion of a fluid
Irreversible processes examples Adding friction and viscosity make things irreversible: Effect of friction is to convert mechanical energy to heat energy. e.g. heating of a particle due to friction.	**Irreversible processes examples** • Spontaneous transfer of heat from hot body to cold body: e.g. all the mixing problems • Ice melting to give water at same temperature

Adiabatic processes:

A process is called adiabatic under following cases:
If we isolate a system from the rest of the universe, (e.g. Dewar flasks for gases)
then heat cannot flow into or out of the system.
Under compression gases heat up and under expansion they cool.

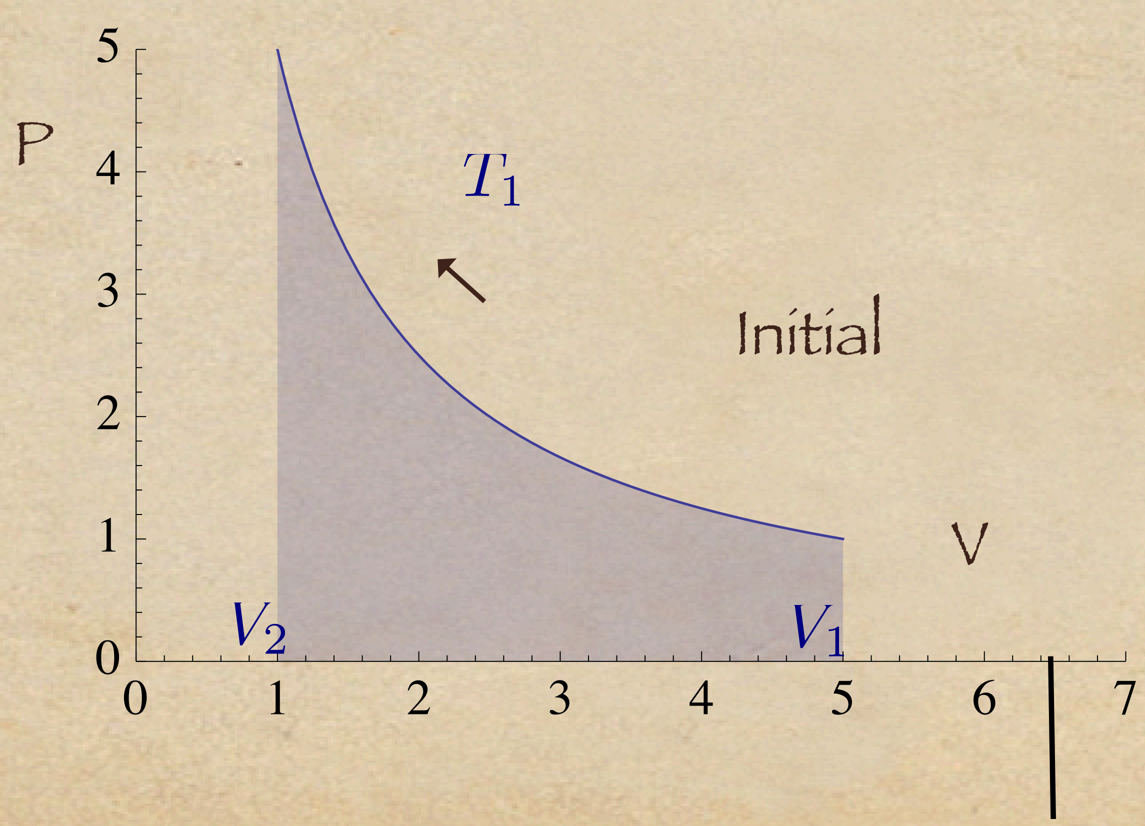
Example: Sound waves in a medium consist of expansion and rarefaction in a short time interval. They travel too fast to gain heat or supply heat to environment hence are adiabatic.
Elastic band can be pulled many times quickly and heats up: adiabatic since heat energy cannot escape fast enough. This may be regarded as an irreversible adiabatic process, irreversible since heat is produced.

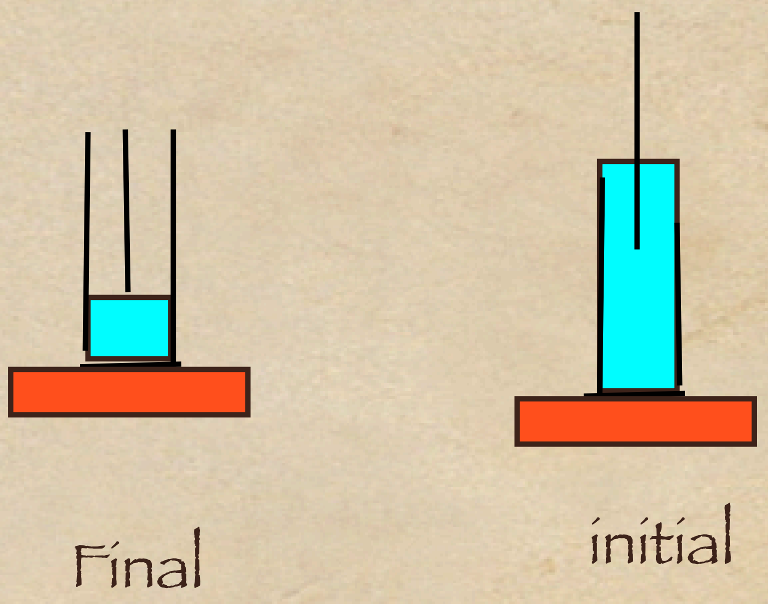
For Carnot engines, adiabatic is taken to mean expansion or compression in isolation, hence
the temperature of the fluid can and does change. Unlike the elastic band, this expansion is carried out very slowly so that the process is reversible.

Isothermal process:

These are processes where the temperature is maintained by some agency, e.g. a heater or hot plate that acts as a reservoir.

The energy of the system is not fixed here, heat can and does flow into the fluid from the reservoir.

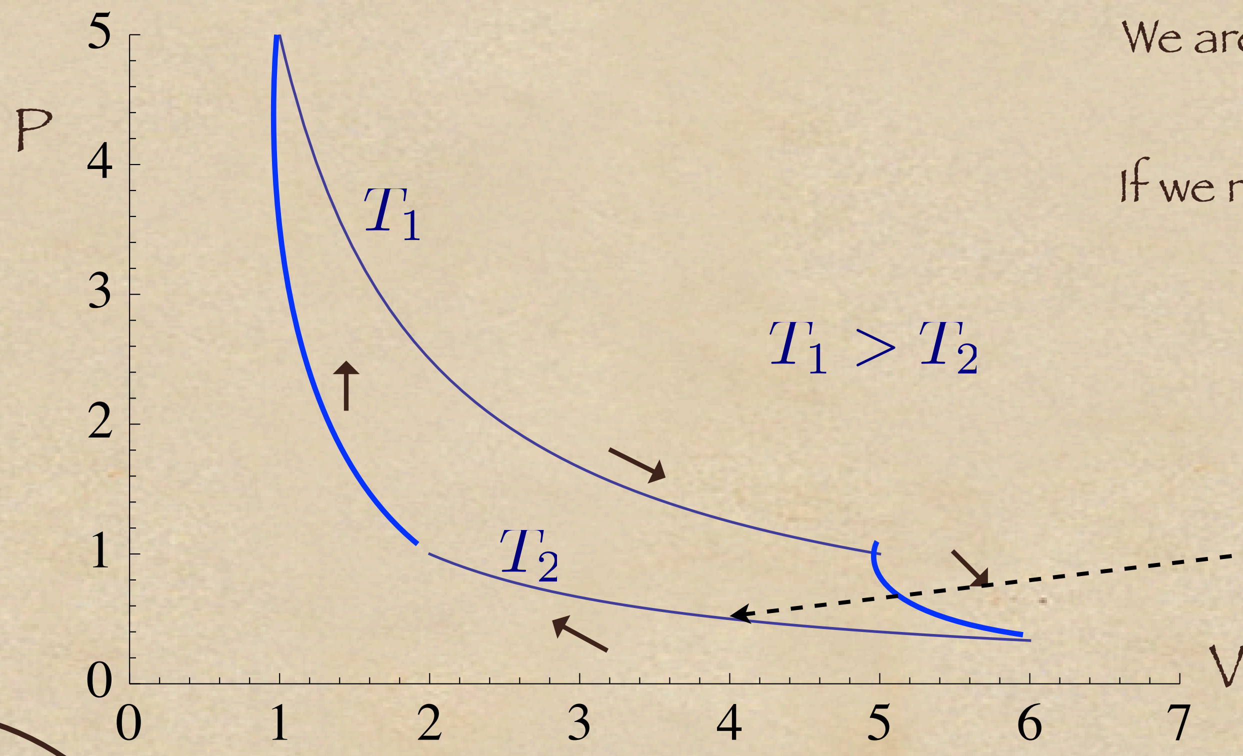


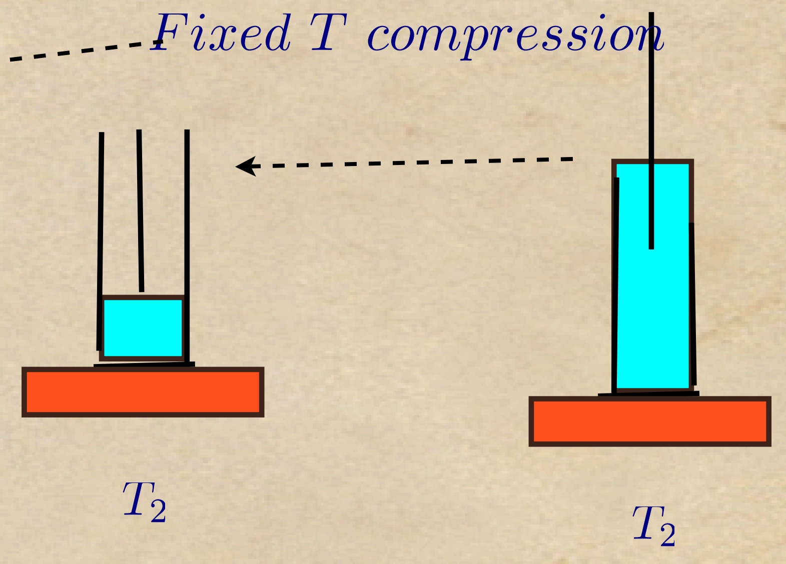


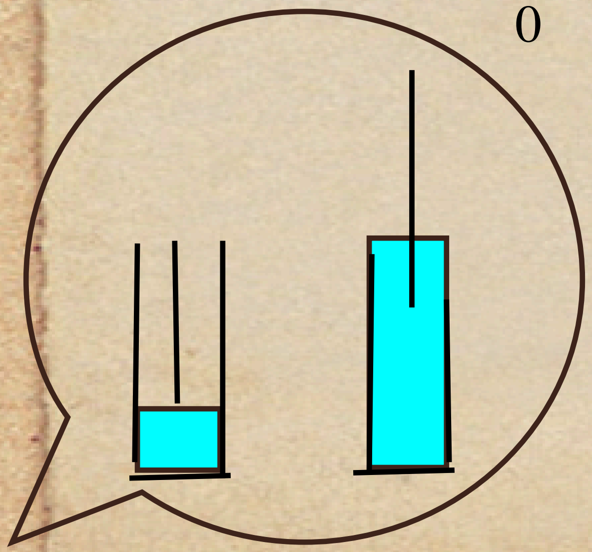
Ideal Heat Engine

Work done on the fluid
is the shaded area.
What about the sign?
Sign depends upon the direction of
traversing the cycle.

In the case illustrated here:
total work done on fluid is positive:
We are doing the opposite of a heat engine
here, it is a heat pump.
If we reverse the direction of arrows, we get
the Carnot heat engine







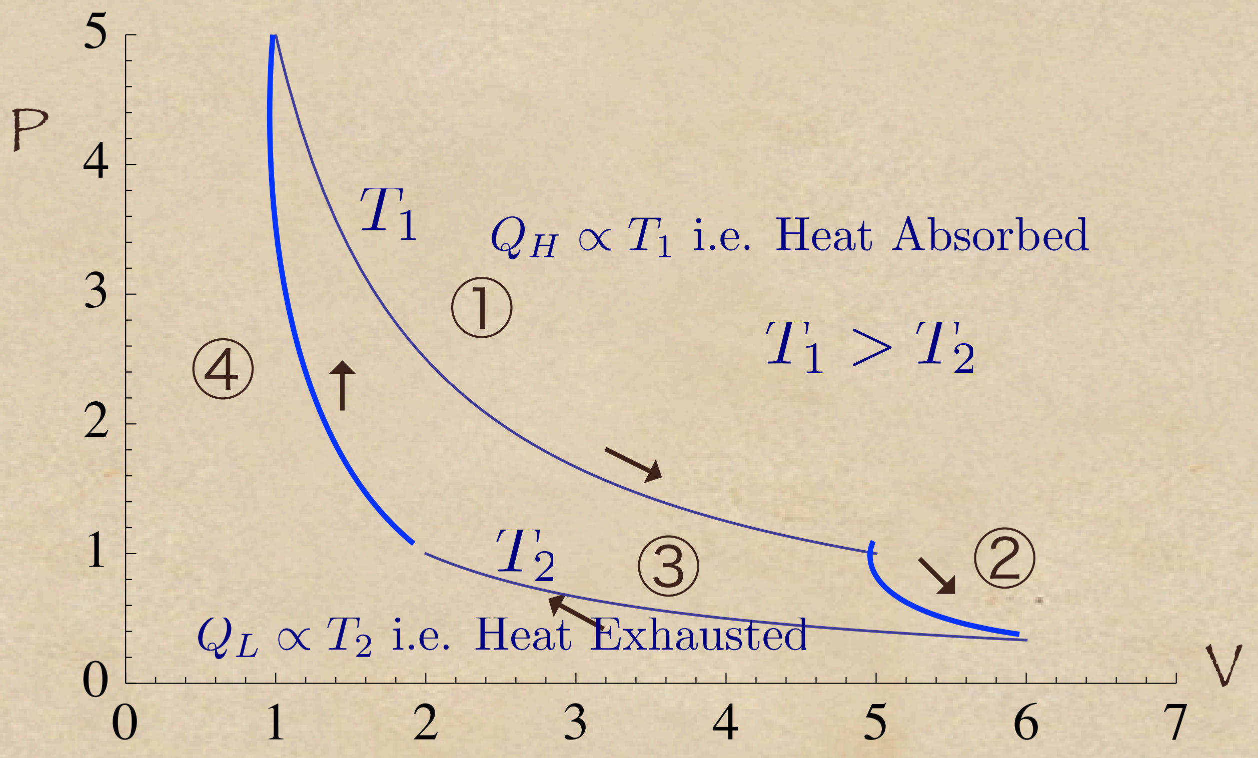
Adiabatic Expansion or Compression

(1) Isothermal expansion: Fluid extracts heat from reservoir and does work on external body ($\Delta V > 0$ hence work done on fluid is negative i.e. fluid works on the environment).

(2) Adiabatic expansion: continues to do work but cools down to lower Temp T_2

(3) Do work on fluid at lower temp isothermally. We are compressing the fluid

(4) Continue to compress adiabatically: temperature rises back to T_1 so we are back to original state.



$$Q_L = Q_{Cold} \quad Q_H = Q_{Hot}$$

$$Q_H \propto T_H$$

$$Q_L \propto T_L$$

$$W = Q_H - Q_L$$

First Law

$$\eta = \text{Work done (usefully)}/InputHeat = \frac{T_H - T_L}{T_H}$$

Heat Pump≈Refrigerator
≈ Heat Engine Run backwards

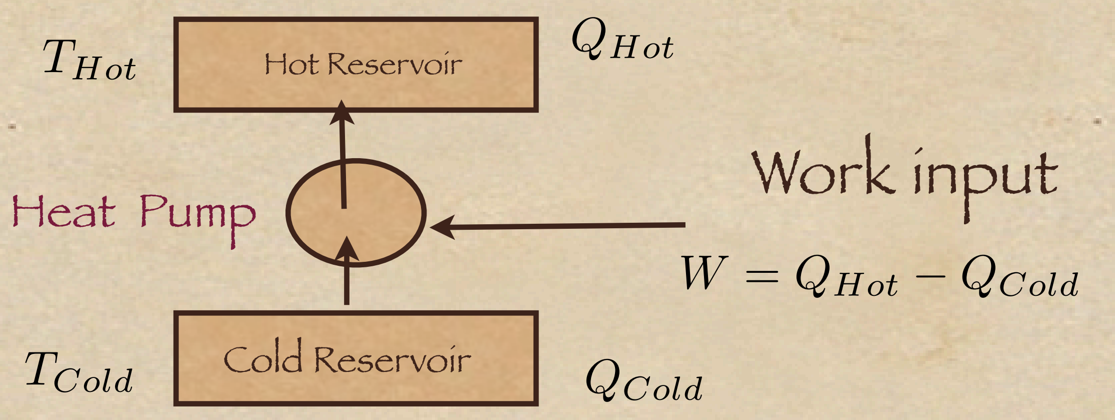
Coefficient of Performance:

$$COP = \frac{Q_{Hot}}{Q_{Hot} - Q_{Cold}} \times 100\%$$

Often COP > 500% or 600%

Outside temperature of room containing the refrigerator

Warm bedroom inside house



T_{Hot} Hot Reservoir Q_{Hot}

Heat Pump

Work input

$W = Q_{Hot} - Q_{Cold}$

T_{Cold} Cold Reservoir Q_{Cold}

Cold outside air in winter

Cold milk in refrigerator

Remarkable fact is that

$W < Q_{Hot}$, i.e. we are getting Q_{Hot} amount of heat although putting in only W by our external agencies.

Good alternative to space heaters.