Lecture 2.6

The Second Law
…contd

…..understanding entropy

Entropy is a thermodynamic property which decides adiabatic accessibility of states

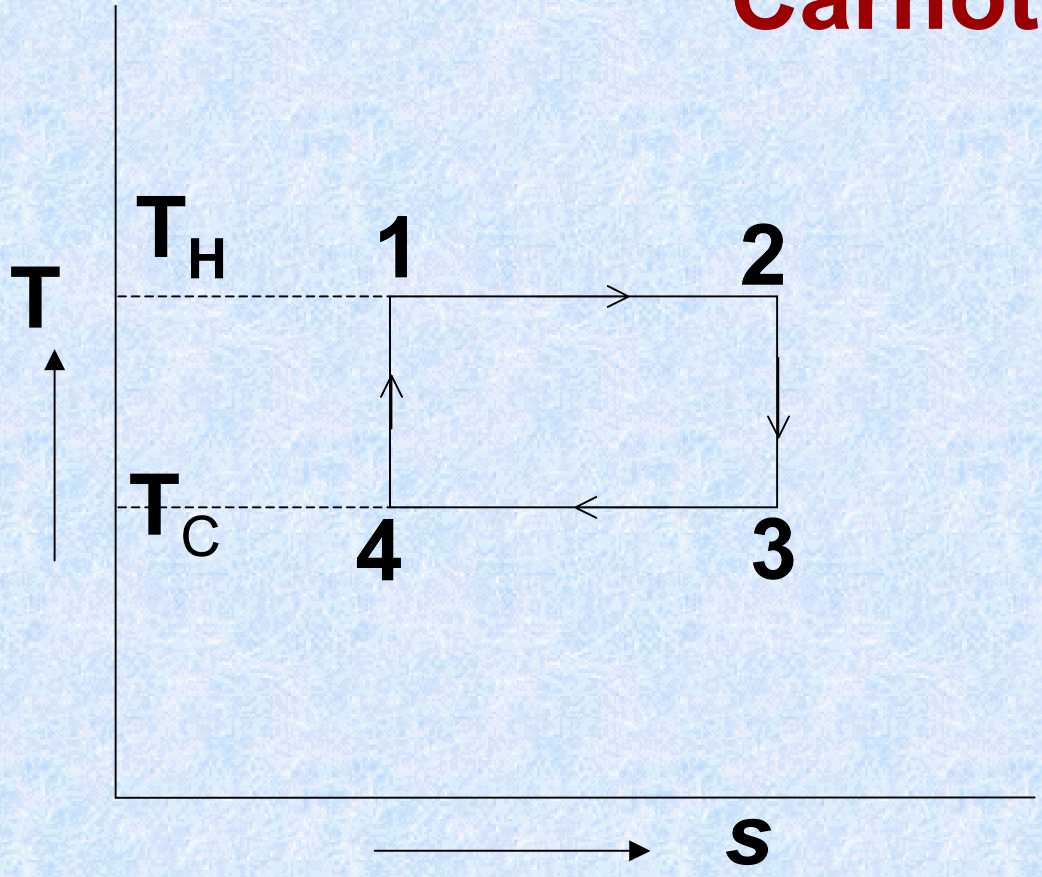
In a reversible process

$$\Delta S = \frac{\Delta Q}{T}$$

T should be absolute temperature !

The Concept of Absolute Temperature

Carnot Cycle

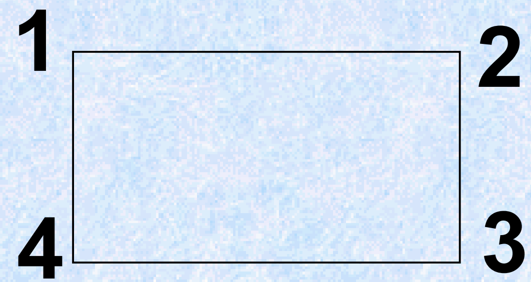


Carnot Cycle…….

Process	Nature	H.T.
1-2	Isoth	Q_H
2-3	Adia	0
3-4	Isoth	$-Q_C$
4-1	Adia	0

Carnot Cycle…….

For 1-2-3-4 to be a cycle



$$s_2 - s_1 = s_3 - s_4$$

or $$\left(s_2 - s_1\right) + \left(s_4 - s_3\right) = 0$$

$$\frac{Q_H}{T_H} - \frac{Q_C}{T_C} = 0 \Rightarrow \frac{Q_H}{Q_C} = \frac{T_H}{T_C}$$

Carnot Cycle…….

$$\therefore \quad \eta_{carnot} = \frac{work\ \ done}{Q_H} = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{Q_C}{Q_H}$$

$$= 1 - \frac{T_C}{T_H}$$

Since η_{carnot} depends only on the value of the two temperatures, above equation enables us to define an absolute temperature scale

Carnot Cycle…….

$$\therefore \quad T_H = T_C \Big/ \left(1 - \eta_{carnot}\right) = T_C \left(\frac{Q_H}{Q_C}\right)$$

Present Convention :choose T_C = 273.16 K for Triple-point of water & determine the 'value' of any temperature from above equation using η_{carnot} as determined experimentally

MEASUREMENT OF ABSOLUTE TEMPERATURE

- Difficulty of building heat engine operating on Carnot cycle
- Need for practically usable methods
- Constant volume gas thermometer
- Platinum resistance thermometers calibrated against easily reproducible states : triple points of O_2, Hg ; M.P. of Ga, Zn etc.

The Concept of Absolute Temperature

- **Achieving Absolute Zero temperature**

- **It can be shown that the definition of absolute temperature (also called Thermodynamic temperature) implies that it is impossible to achieve temperatures below absolute zero.**

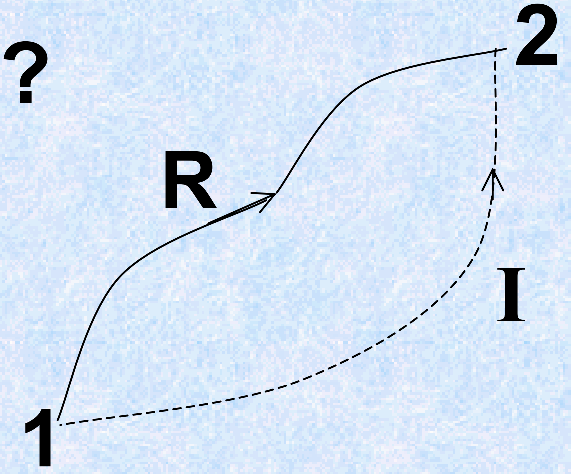
DEFINING ABSOLUTE ZERO TEMPERATURE

If a system undergoes a reversible isothermal process between two reversible adiabatics, without heat transfer, the temperature at which this process takes place is called absolute zero.

ENTROPY CHANGE IN AN IRREVERSIBLE PROCESS

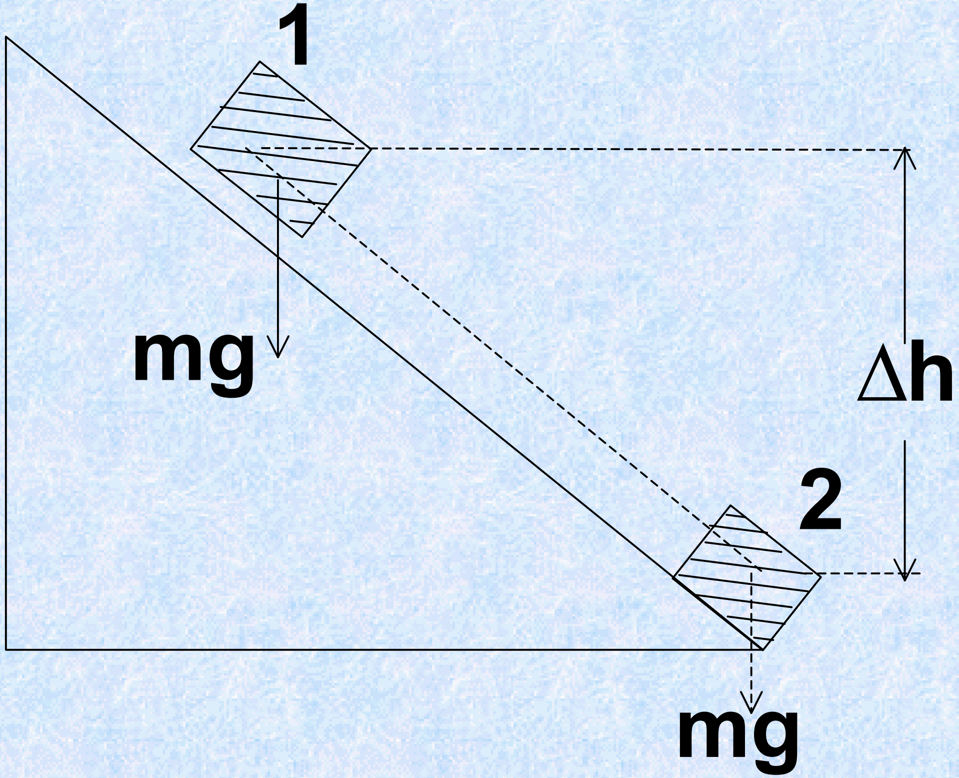
Entropy is a Property ……..?

$$(s_2 - s_1)_I = (s_2 - s_1)_R$$



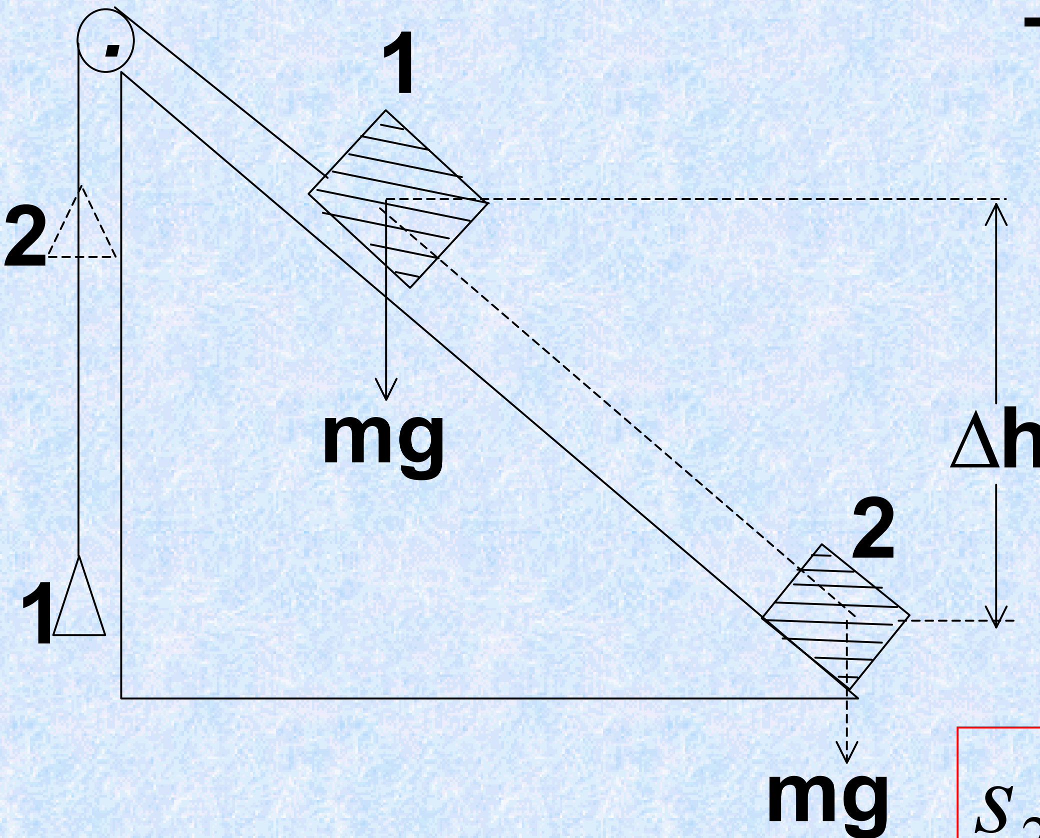
ENTROPY CHANGE IN AN IRREVERSIBLE PROCESS

Entropy Increase due to Friction



ENTROPY CHANGE IN AN IRREVERSIBLE PROCESS

.....due to Friction



$\Delta W_{in} = -mg\ \Delta h$

$\Delta Q_{in} = mg\ \Delta h$

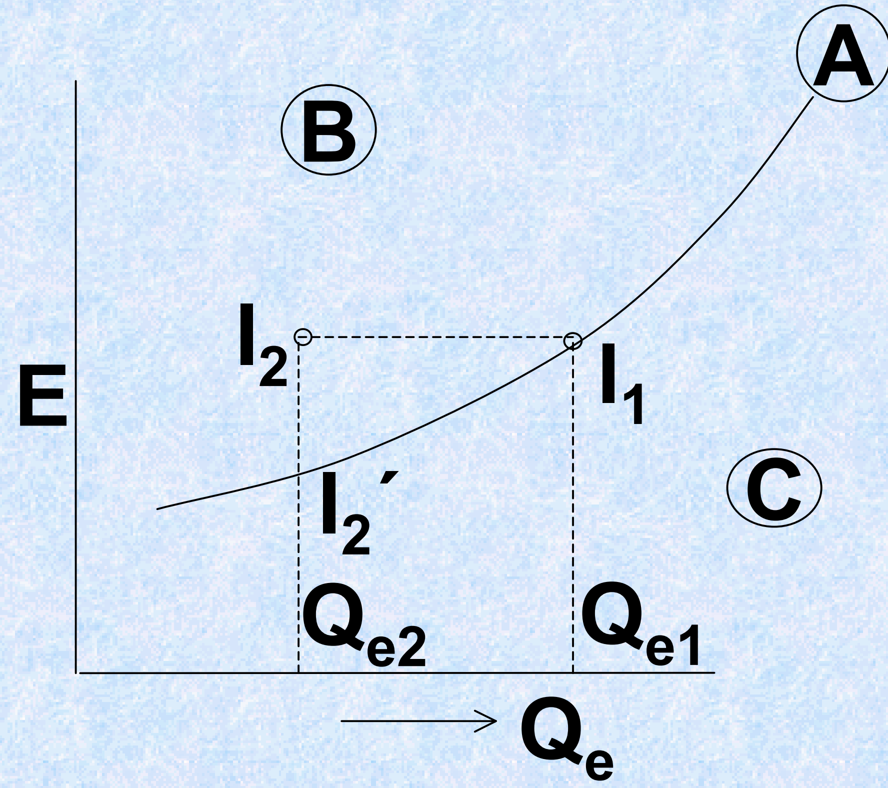
$$s_2 - s_1 = mg\ \Delta h / T$$

ENTROPY CHANGE IN AN IRREVERSIBLE PROCESS

…..due to short-circuiting of a battery

$$W_{on} = \int V dQ_e = V_{avg}(Q_{e2} - Q_{e1})$$

$$s_2 - s_1 = \frac{Q_{avg}}{T_{avg}} = \frac{V_{avg}(Q_{e1} - Q_{e2})}{T_{avg}}$$



ENTROPY CHANGE IN AN IRREVERSIBLE PROCESS

Other examples

- **Free expansion of a compressible fluid**
- **Heat transfer between two reservoirs having finite temperature difference**

End of Lecture

Lecture 2.7

The Second Law
…..Corollaries

.......Recap

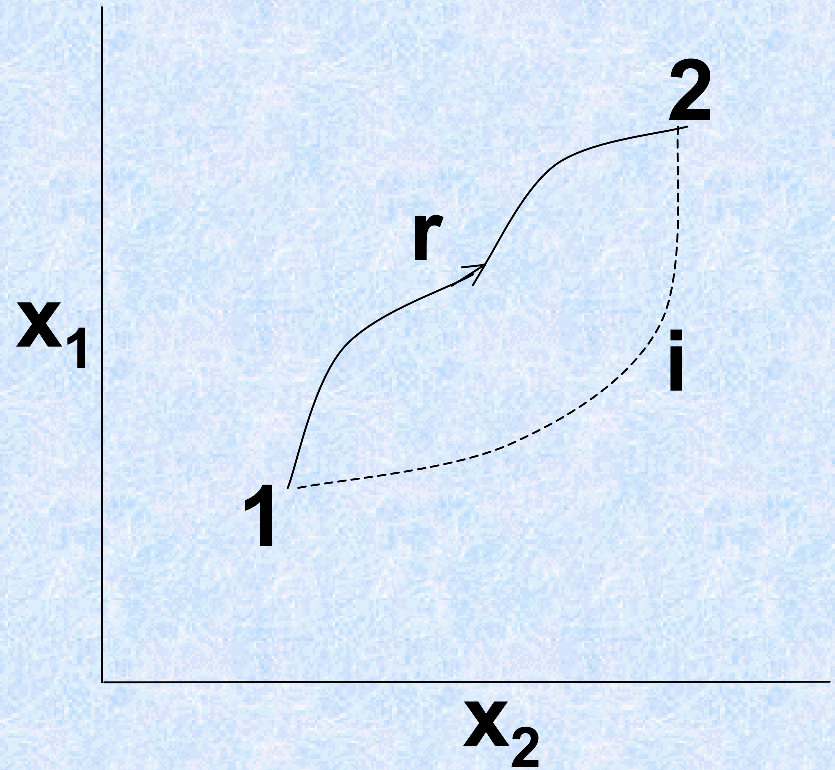
- Caratheodory's formulation of 2nd Law
- Reversible & Irreversible processes
- Concept of Entropy
- Concept of Absolute Temperature
- Entropy change in an irreversible process

Work done in an Irreversible Process

r : $\Delta E = \Delta Q_r + \Delta W_r$

i : $\Delta E = \Delta Q_i + \Delta W_i$

$\Delta W_i = \Delta W_r + \Delta Q_r - \Delta Q_i$



Is $\Delta Q_r - \Delta Q_i$ > < = 0?

Work done in an Irreversible Process

* Assume 1 - 2 in close proximity so that the temp T doesn't change much during the process

- Δ S is same in both the processes
- $\Delta Q_r = T \Delta S$

$$\therefore \Delta Q_r - \Delta Q_i = T \Delta S - \Delta Q_i$$

Work done in an Irreversible Process

Consider the 3 possibilities

$$T \Delta S - \Delta Q_i > 0$$

$$T \Delta S - \Delta Q_i < 0$$

or

$$T \Delta S - \Delta Q_i = 0$$

Which of these two is correct ?

X

Process I is irreversible & this eq. is valid only for reversible process.

Work done in an Irreversible Process

Since above discussion is general, it should also apply to the special case of an adiabatic process, i.e. $\Delta Q_i = 0$

For this special case, these inequalities give

$$T \Delta S > 0 \quad \text{or} \quad T \Delta S < 0$$

Which is correct ?

Work done in an Irreversible Process

Since in an irreversible adiabatic process the entropy can only increase

$$\therefore T \Delta S > 0$$

Therefore for any irreversible process

$$T \Delta S - \Delta Q_i > 0$$

$$\Delta S > \Delta Q_i/T$$

Recall, for a reversible process

$$\Delta S = \Delta Q_r/T$$

Work done in an Irreversible Process

$$T\Delta S - \Delta Q_i \quad > \quad 0$$

$$\Delta Q_r - \Delta Q_i \quad > \quad 0$$

$$\Delta W_i \quad > \quad \Delta W_r$$

$$\left(-\Delta W_i\right) \quad < \quad \left(-\Delta W_r\right)$$

Work output in an irreversible process is smaller

Work input in irreversible process is greater

Work done in an Irreversible Process

Conclusion : Starting from a given initial state, to reach the same final state work input required is larger in an irreversible process.

In a work producing cycle $W_{irr} < W_{rev}$

Work done in an Irreversible Process

Condition under which this result is derived?

Pts 1-2 close to each other, $T \approx T_1 \approx T_2$

= temp of thermal reservoir

It is possible to have work output in an irreversible process > that in a reversible process between the same end states

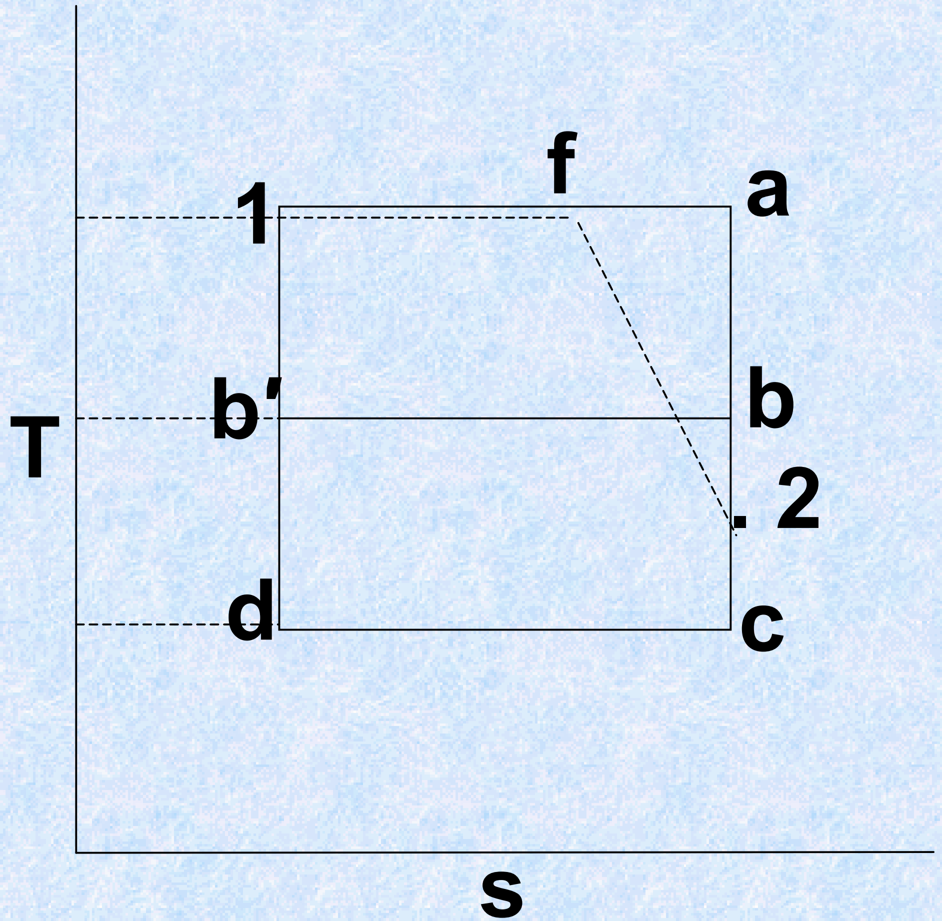
Work done in an Irreversible Process

Reversible paths

1 - a - 2

1- b′ - b - 2

1 - c′ - c - 2



Work done in an Irreversible Process

$T_a > T_b > T_C$ $\qquad$ $Q_a > Q_b > Q_C$

- $E_2 - E_1 = Q_a + W_{ona} = Q_b + W_{on,b} = Q_C + W_{on,c}$

$\therefore W_{on,a} < W_{on,b} < W_{on,c}$

$\Downarrow$

$W_{by,a} > W_{by,b} > W_{by,c}$

since $E_2 < E_1$

W_{on} is -ve

1-f-2 irreversible $\quad W_{by,f} < W_{by,a}$

But $W_{by,f}$ can be $> W_{by,c}$!

BASIC EQ. OF THERMODYNAMICS

Combining the expressions for entropy change in reversible and irreversible processes

$$dS \geq \frac{dQ}{T} \geq \frac{dE - dW}{T}$$

$$\geq \frac{\left(dE + \Sigma f_i'' dx_i''\right)}{T}$$

BASIC EQ. OF THERMODYNAMICS

$$TdS \geq dE + \Sigma f_i'' dx_i''$$

$$TdS \geq dE - \Sigma f_i'' dx_i'$$

$$\{If \; dx_i' = - dx_i''$$

For a reversible process $f_i'' = f_i'$

BASIC EQ. OF THERMODYNAMICS

For a reversible process

$$TdS = dE - \Sigma f_i' dx_i'$$

↑

Basic equation of thermodynamics applicable to all processes !!

End of Lecture

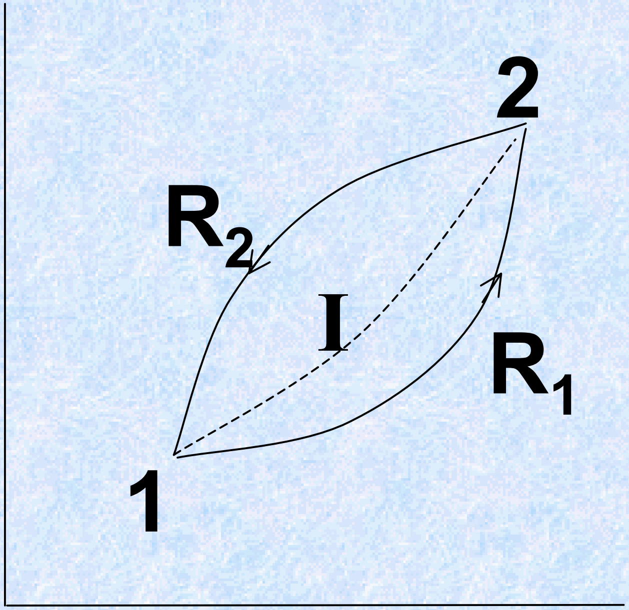
Lecture 2.8

The Second Law
…..Corollaries

SECOND LAW FOR CYCLIC PROCESSES

For all cycles

$$\oint dS = 0$$



for reversible cycle $R_1 - R_2$

$$dS = \frac{dQ}{T} \Rightarrow \int dS = \int \frac{dQ}{T}$$

$$\therefore \oint dS = 0 \Rightarrow \oint \frac{dQ}{T} = 0 ------ I$$

SECOND LAW FOR CYCLIC PROCESSES

For irreversible cycle I – R_2

Process I

$$dS > \frac{dQ}{T} \Rightarrow \int_I dS > \int_I \frac{dQ}{T}$$

Process R_2

$$dS = \frac{dq}{T} \Rightarrow \int_{R_2} dS = \int_{R_2} \frac{dq}{T}$$

SECOND LAW FOR CYCLIC PROCESSES

For irreversible cycle I – R_2

$$\therefore \oint dS = \int_I dS \quad + \int_{R_2} dS \quad > \oint \frac{dQ}{T}$$

$$\int \frac{dQ}{T} < 0 ------II$$

SECOND LAW FOR CYCLIC PROCESSES

Combine I & II to get

$$\oint \frac{dQ}{T} \leq 0$$

Clausius Inequality

Applying to power cycles

$$\frac{Q_h}{T_h} - \frac{Q_C}{T_C} \leq 0$$

or

$$\frac{Q_h}{Q_C} \leq \frac{T_h}{T_C} \quad ; \quad \frac{Q_C}{Q_h} \geq \frac{T_C}{T_h}$$

SECOND LAW FOR CYCLIC PROCESSES

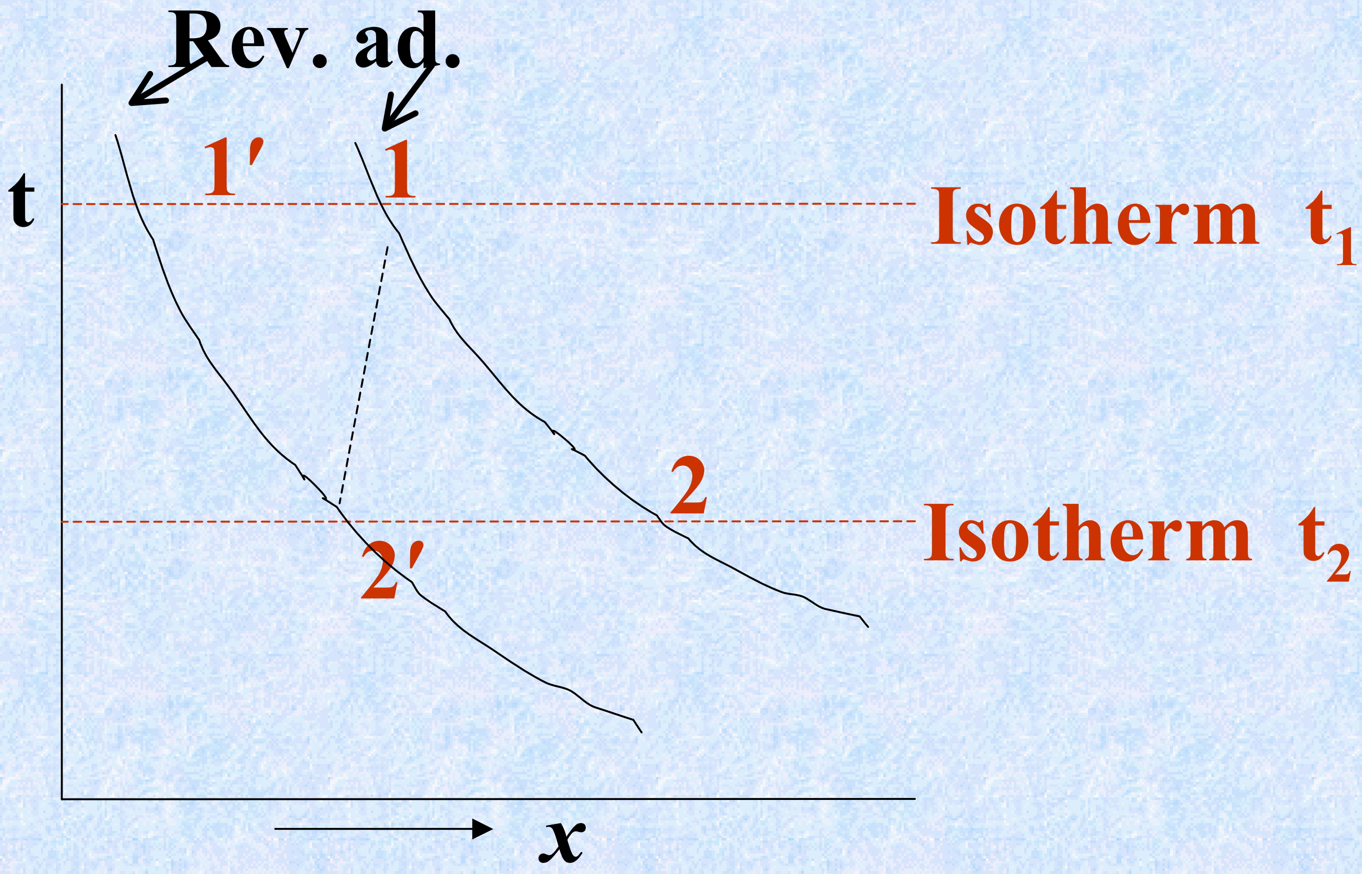
$$\therefore \eta = 1 - \frac{Q_C}{Q_h} \leq 1 - \frac{T_C}{T_h}$$

$\Rightarrow$ **(η<1) :Kelvin Planck Statement of 2nd Law**

Carnot Cycle (Reversible Engine) is the most efficient in conversion of heat to Work.

Similarly derive Clausius Statement of 2nd Law by considering a Reversed CC.

EQUIVALENCE OF CARATHEDORY'S FORMULATION with Kelvin-Planck Statement

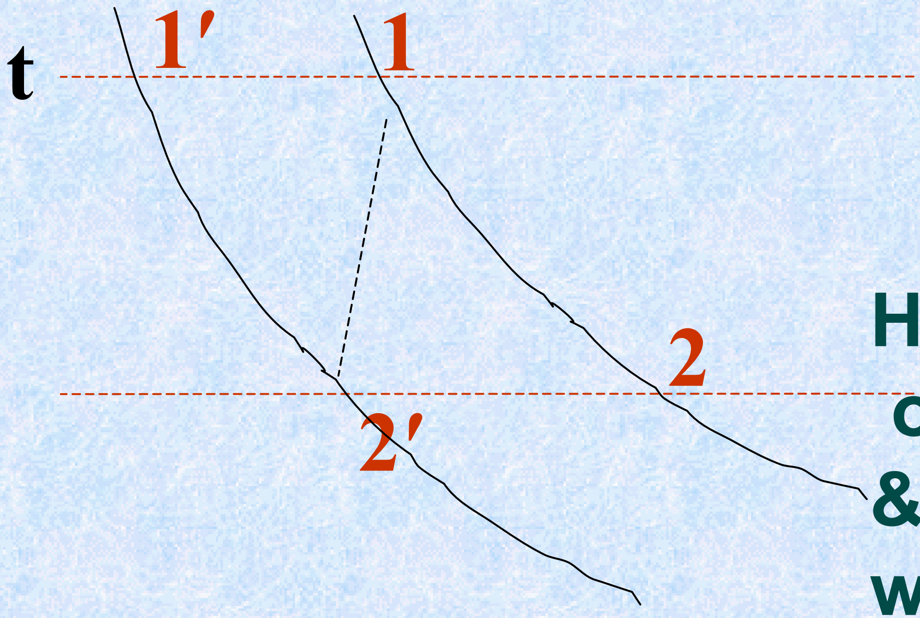


EQUIVALENCE OF CARATHEDORY'S FORMULATION with Kelvin-Planck Statement

Caratheodory: 2' inaccessible adiabatically from 1

Suppose this is not true i.e. 2' is then adiabatically accessible from 1 (say process 1-2')

EQUIVALENCE OF CARATHEDORY'S FORMULATION WITH Kelvin-Planck Statement



Consider

Cycle 1-2'-1'-1

Heat absorbed from only one reservoir at t_1 & equal amount of work is produced

THIS VIOLATES K-P STATEMENT

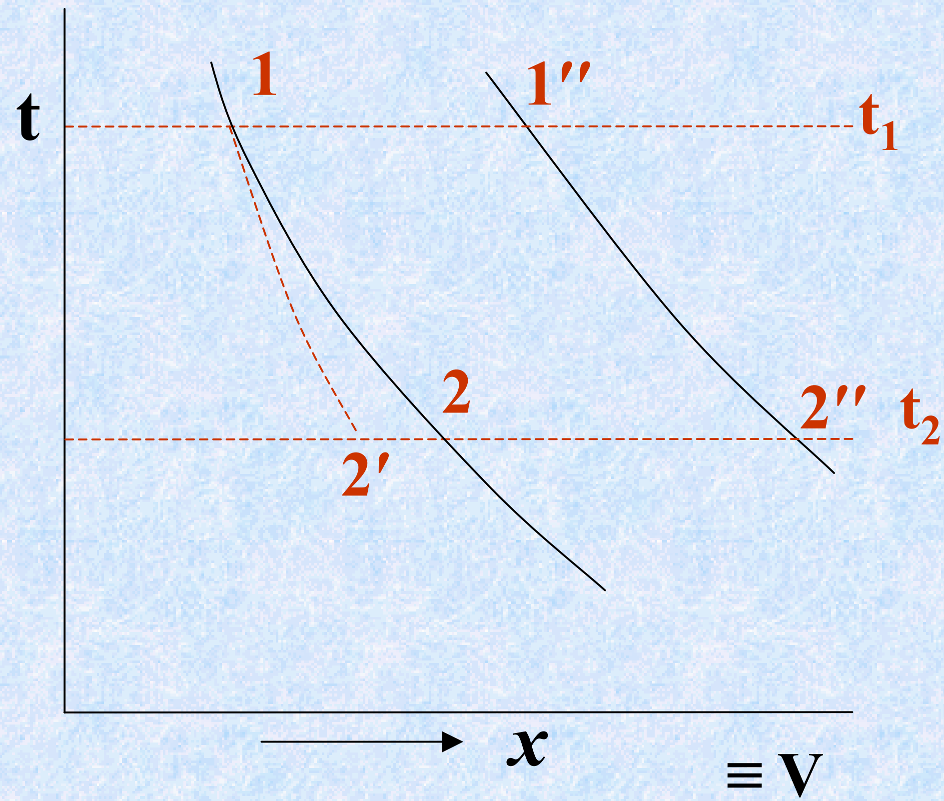
Equivalence of Caratheodory's formulation with Clausius Statement

Caratheodory : 1-2′ can't be an adiabatic process

<u>NB</u> 2′ has been so located that

$Q_{1-1''} = Q_{2'-2''}$

{both +ve}

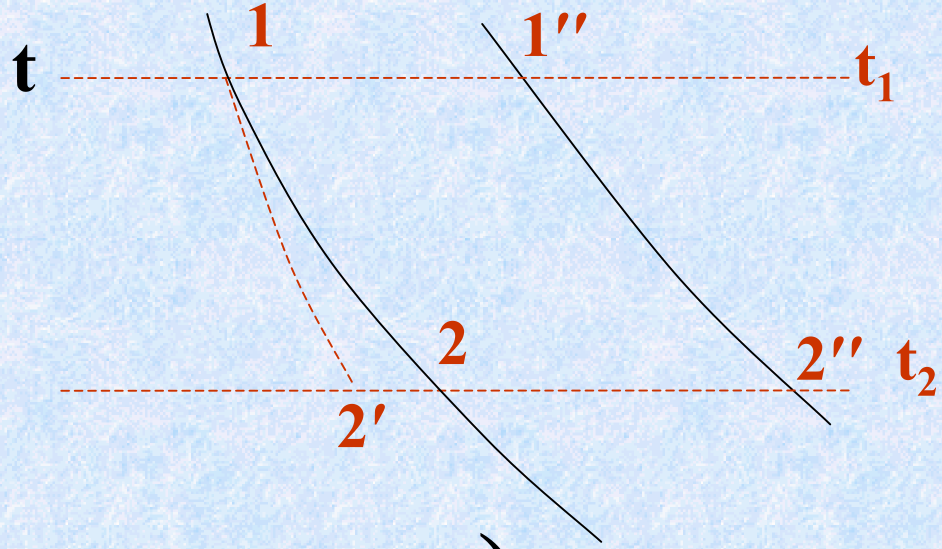


Equivalence of Caratheodory's formulation with Clausius Statement

Assuming Caratheodory's axiom is incorrect 1-2' could be an adiabatic process.

Then consider cycle 1- 2'- 2" -1"– 1

It has two heat transfers, viz



$$Q_{2'2''} \rightarrow +ve$$

$$Q_{1''-1} \rightarrow -ve$$

$$\Sigma\left(Q_{1''-1} + Q_{2'2''}\right) = 0$$

Equivalence of Caratheodory's formulation with Clausius Statement

$Q_{net} = 0 = W_{net}$ $\Rightarrow$ Heat $|Q_{2'2''}|$ has been absorbed at low temp. t_2 & delivered to high temp. t_1, without any work input

↓

VIOLATION OF CLAUSIUS STATEMENT

End of Lecture

Lecture 2.9

The Second Law …..Corollaries & Applications

ENTROPY MAX PRINCIPLE

for any process

$$dS \geq \frac{dQ}{T} \quad \Rightarrow dS = \frac{dQ}{T} + d\sigma$$

$$where \quad d\sigma \geq 0$$ $\equiv$ **entropy gen.**

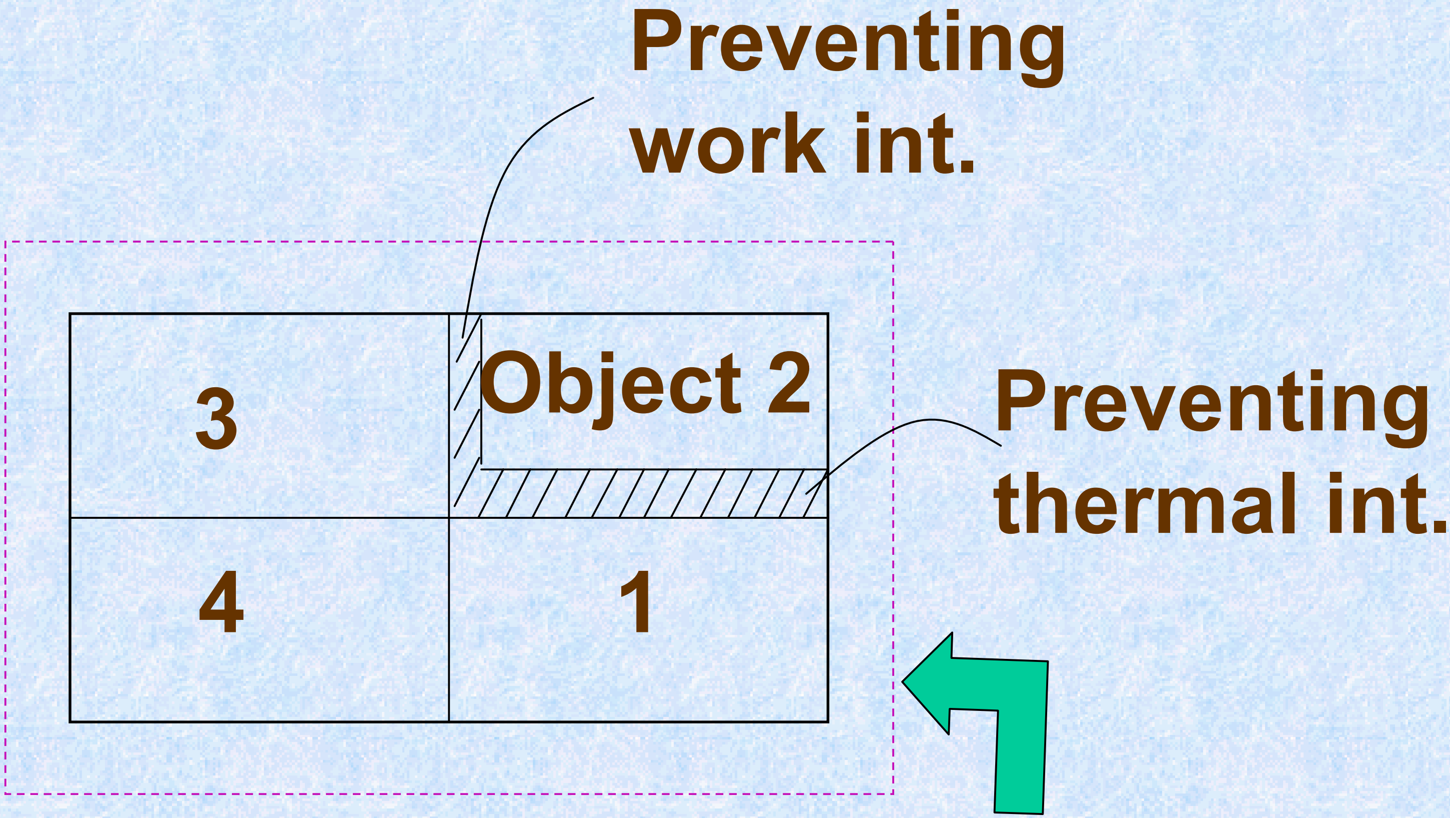
In rate terms: $$\frac{dS}{dt} = \frac{\dot{Q}}{T} + \frac{d\sigma}{dt} = \frac{\dot{Q}}{T} + \dot{\sigma}$$

In the absence of thermal interaction

$$ds = d\sigma \geq 0$$

Principle of Increase of entropy

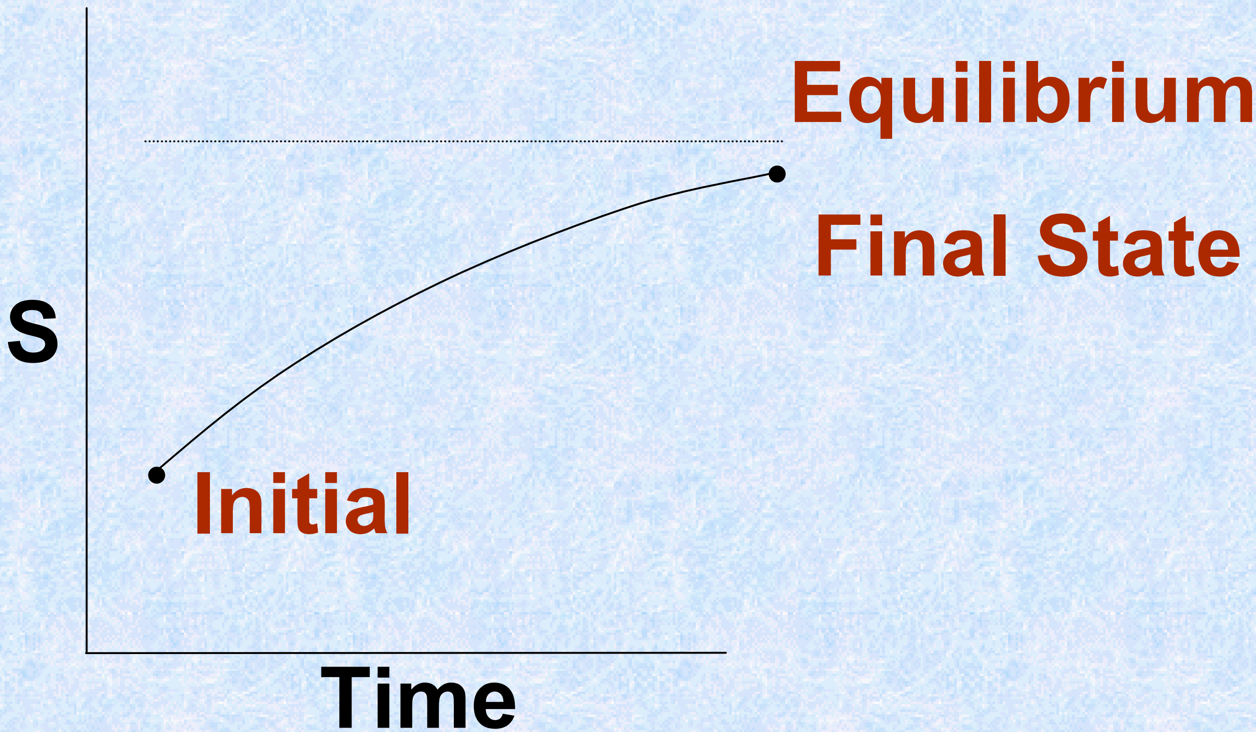
ENTROPY MAX PRINCIPLE



Composite system is isolated

The entropy reaches maximum possible value at the equilibrium

ENTROPY MAX PRINCIPLE

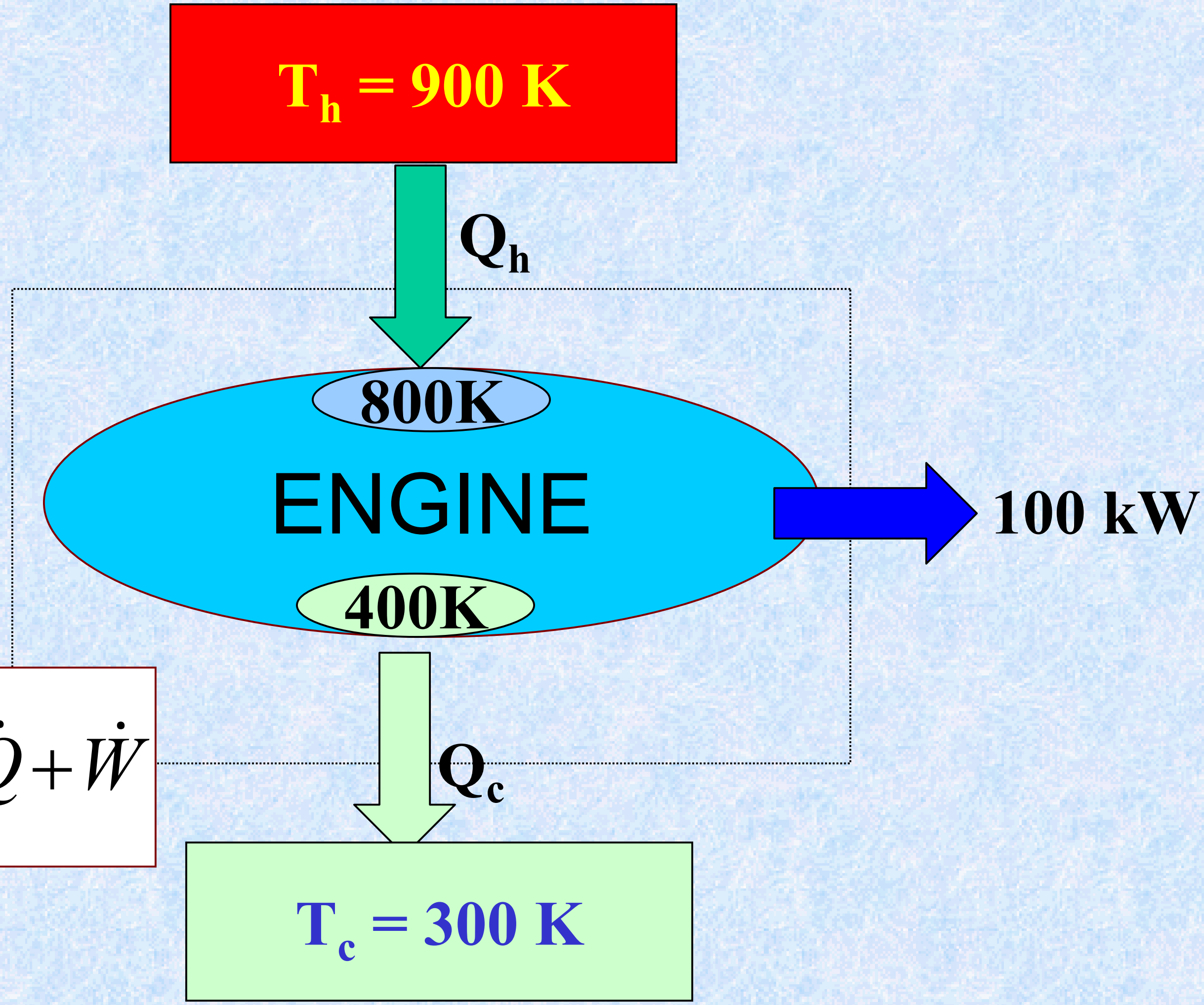


Trend to Equilibrium

Examples of Second Law Analysis

A heat engine operates in a cycle between two thermal reservoirs at 300K and 900K and produces 100kW power. Find the heat rejection and entropy generation when the engine is internally reversible but receives heat and rejects heat at 800K and 400k respectively

First Law in rate terms:



$$\frac{dE}{dt} = \frac{dQ}{dt} + \frac{dW}{dt} = \dot{Q} + \dot{W}$$

For this cycle:

$0 = \Sigma Q - 100$

$Q_h - Q_c = 100$

Since the engine is internally reversible : $Q_h/800 - Q_c/400 = 0$

$Q_h = 200kW$

$Q_c = 100kW$

Example 1….

Second Law in rate terms:

$$\frac{dS}{dt} = \sum \frac{\dot{Q}}{T} + \frac{d\sigma}{dt}$$

For this cycle :

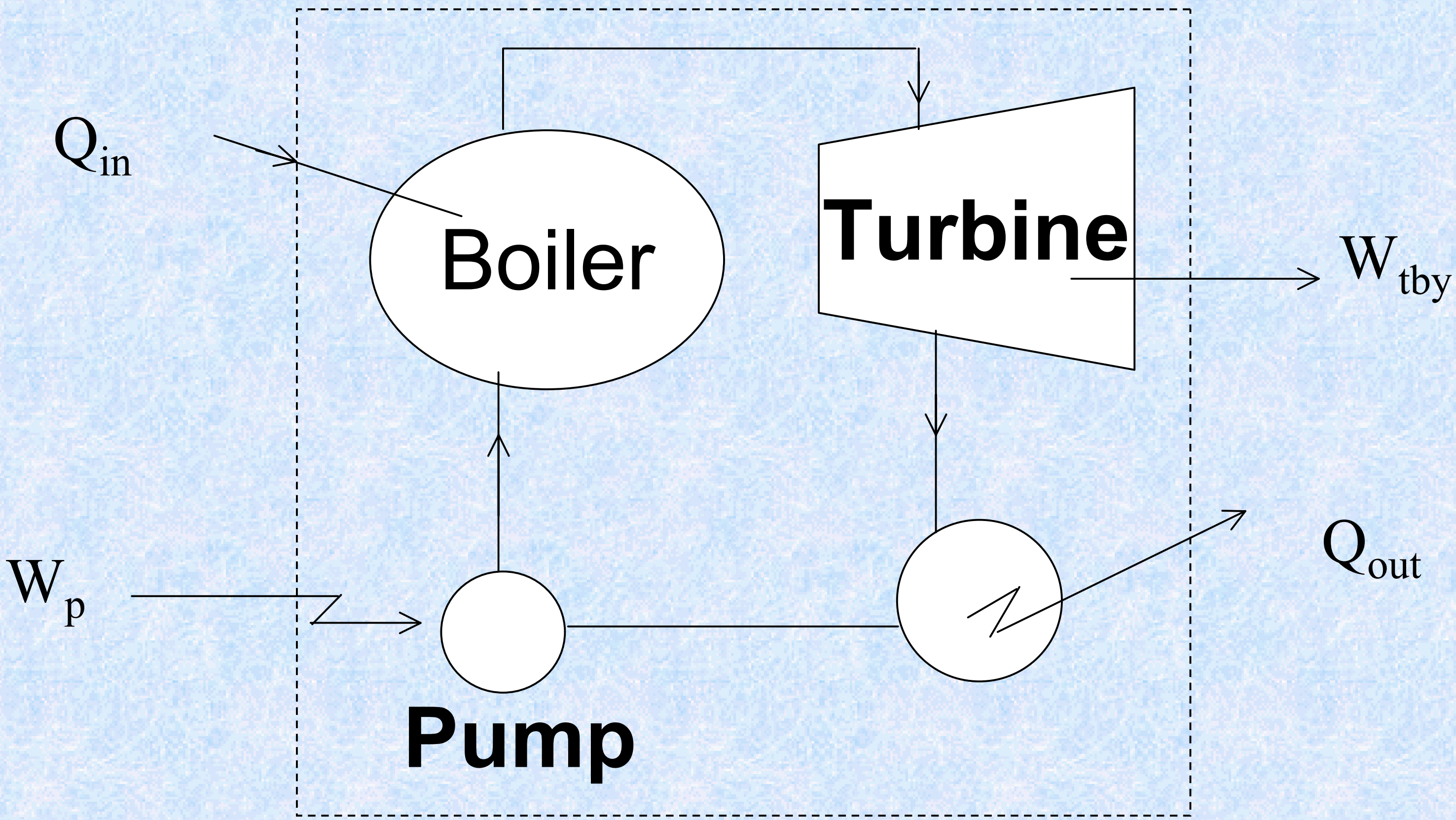
$$\frac{d\sigma}{dt} = -\langle \frac{Q_h}{900} - \frac{Q_C}{300} \rangle$$

This gives entropy generation rate as:
-[200/900 - 100/300] = 0.111 kW / K

EXAMPLE 2

A simple steam power cycle producing 100 MW of power receives heat at 900K in the boiler and rejects heat at 320K. The condensate pump consumes 50kW of power, and the boiler consumes 54 tonnes/hour of coal. Assuming that the combustion of 1Kg of coal releases 20MJ of heat determine the thermal efficiency and entropy generation in the cycle.

EXAMPLE 2……



EXAMPLE 2 ....

First Law (for System within dashed line boundaries)

$$\frac{dE}{dt} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{P_{in}} - \dot{W}_{T,by}$$

Under steady state conditions, $\frac{dE}{dt} = 0$

$$\Rightarrow \dot{Q}_{in} - \dot{Q}_{out} = \dot{W}_{T,by} - \dot{W}_{P_{in}}$$

Here

$$\dot{Q}_{in} = \frac{54 \times 1000}{3600} \times 20\, MJ/S$$

$$= 300 MW$$

$$\dot{Q}_{out} = 300 - 100$$

$$= 200\ MW$$

$$\eta = \frac{100}{300} = 33.3\%$$

EXAMPLE 2 ……………

Second Law (for system within dashed line boundaries)

$$\frac{dS}{dt} = \Sigma \frac{\dot{Q}}{T} + \dot{\sigma}$$

Under steady state conditions, $\frac{dS}{dt} = 0$

$$\Rightarrow \dot{\sigma} = -\Sigma\left(\frac{\dot{Q}}{T}\right)$$

Here

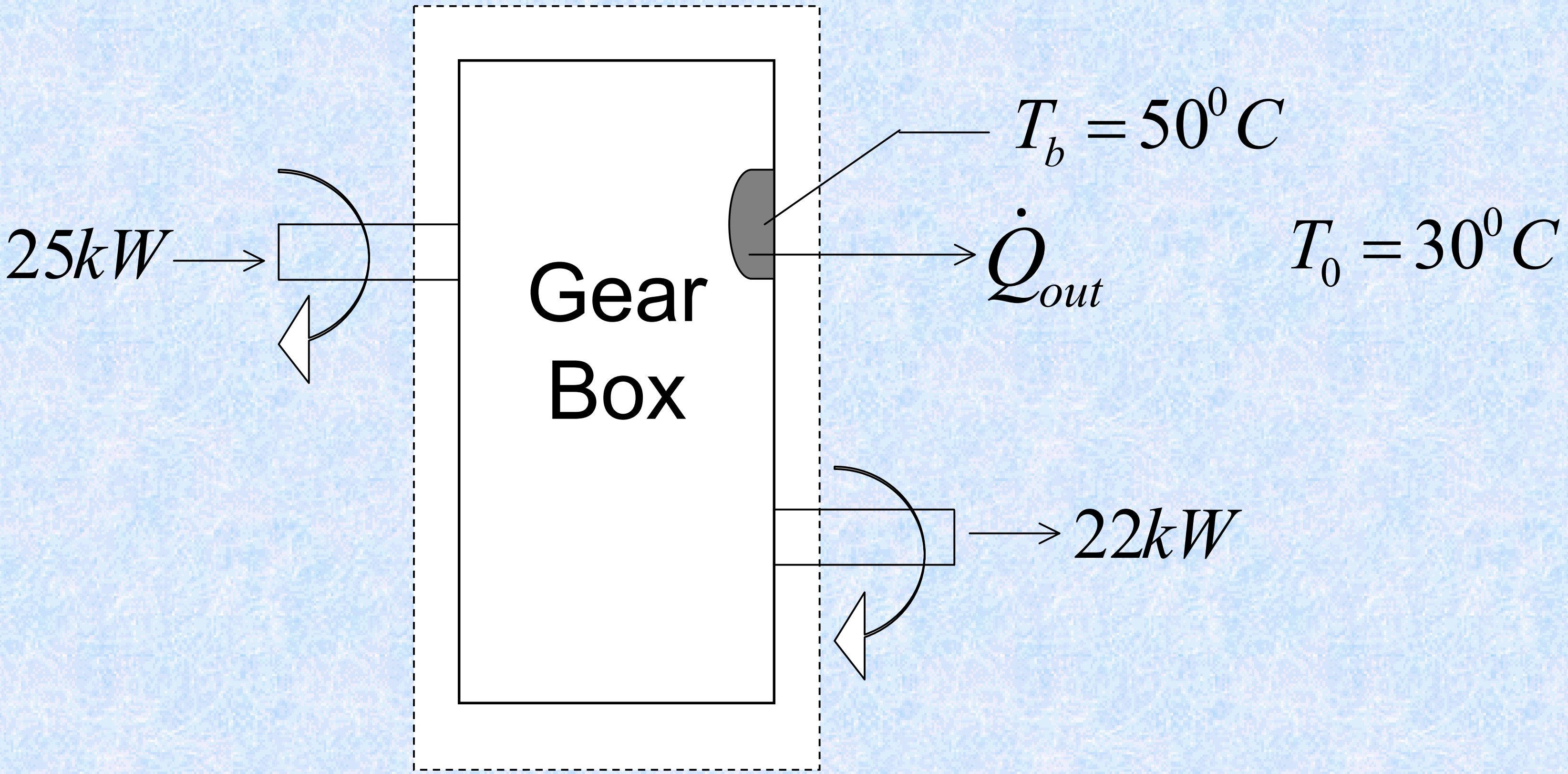
$$\dot{\sigma} = -\left(\frac{300}{900} - \frac{200}{320}\right)\frac{MW}{K}$$

$$= .2917 MW/K$$

EXAMPLE 3

The gear box of a machine is operating under steady-state conditions. The input shaft receives 25 kW from a prime mover and transmits 22kW to the output shaft, the rest being lost due to friction etc. The gear box surface is at an average temperature of 50^0C and loses heat to the surroundings at 30^0C. Estimate the rate of entropy production inside the gear box.

EXAMPLE 3



EXAMPLE 3

Since the gear box is operating in steady state,

First Law $0 = 25 - 22 - \dot{Q}_{out} \Rightarrow \dot{Q}_{out} = 3KW$

Second Law $\dot{\sigma} = -\sum\left(\frac{\dot{Q}}{T}\right) = \frac{\dot{Q}_{out}}{T} = \frac{3 \times 1000}{323} = 9.289\ W/K$

Entropy production outside the box?

End of Lecture

Lecture 2.9

The Second Law …..Corollaries & Applications

ENTROPY MAX PRINCIPLE

for any process

$$dS \geq \frac{dQ}{T} \quad \Rightarrow dS = \frac{dQ}{T} + d\sigma$$

$$where \quad d\sigma \geq 0$$ $\equiv$ **entropy gen.**

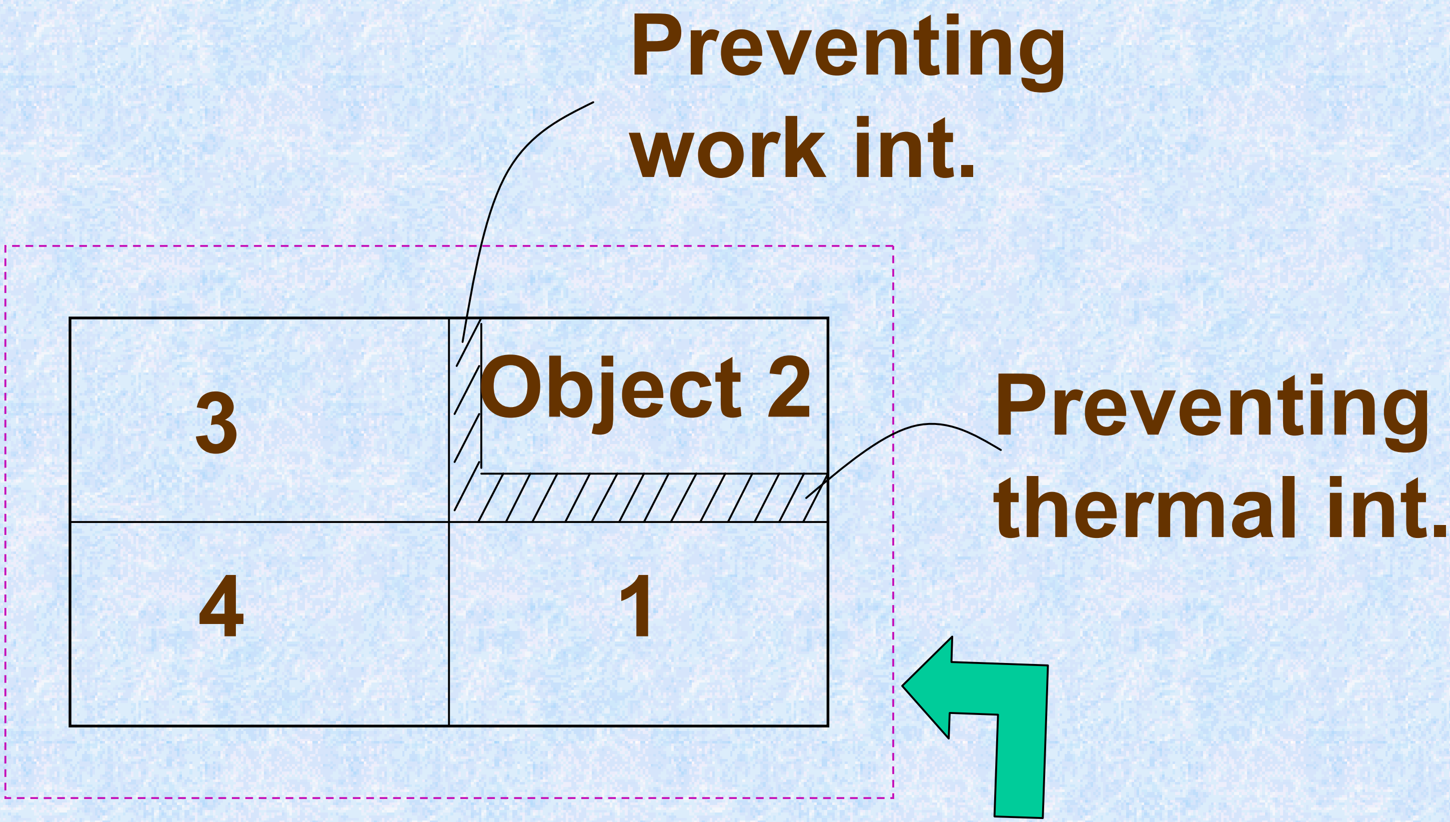
In rate terms: $\frac{dS}{dt} = \frac{\dot{Q}}{T} + \frac{d\sigma}{dt} = \frac{\dot{Q}}{T} + \dot{\sigma}$

In the absence of thermal interaction

$$ds = d\sigma \geq 0$$

Principle of Increase of entropy

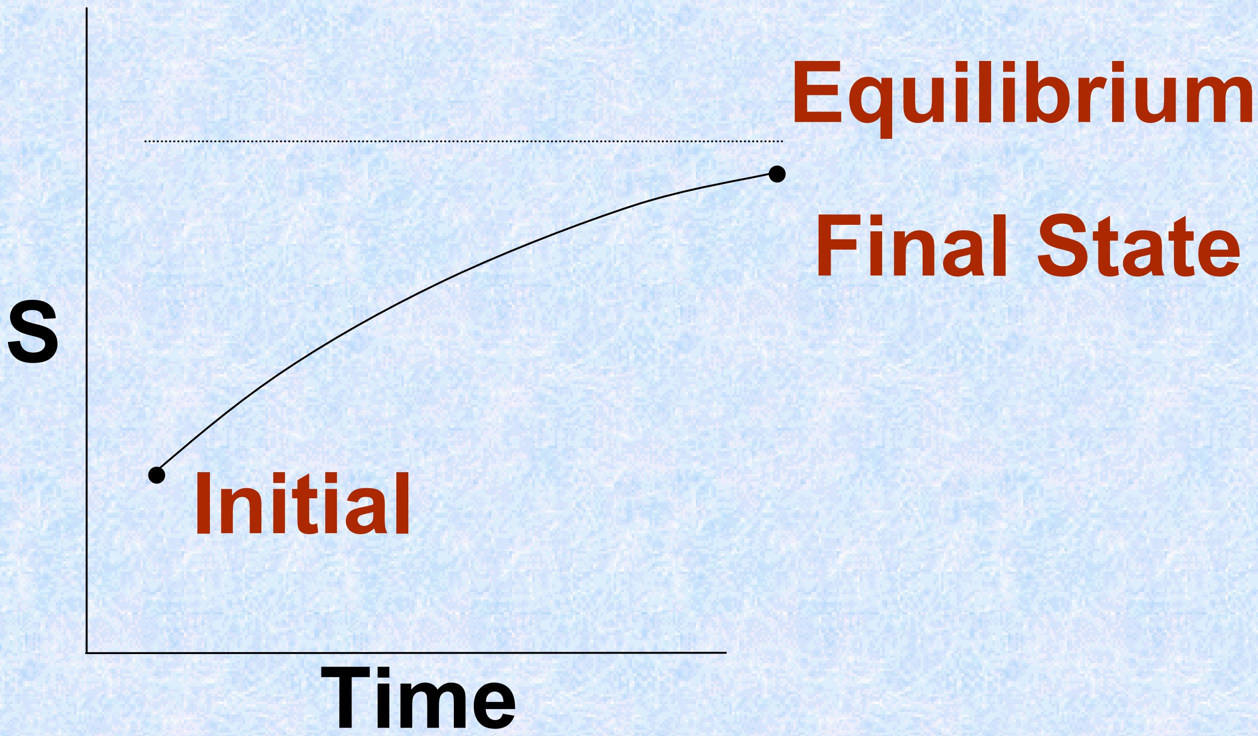
ENTROPY MAX PRINCIPLE



Composite system is isolated

The entropy reaches maximum possible value at the equilibrium

ENTROPY MAX PRINCIPLE

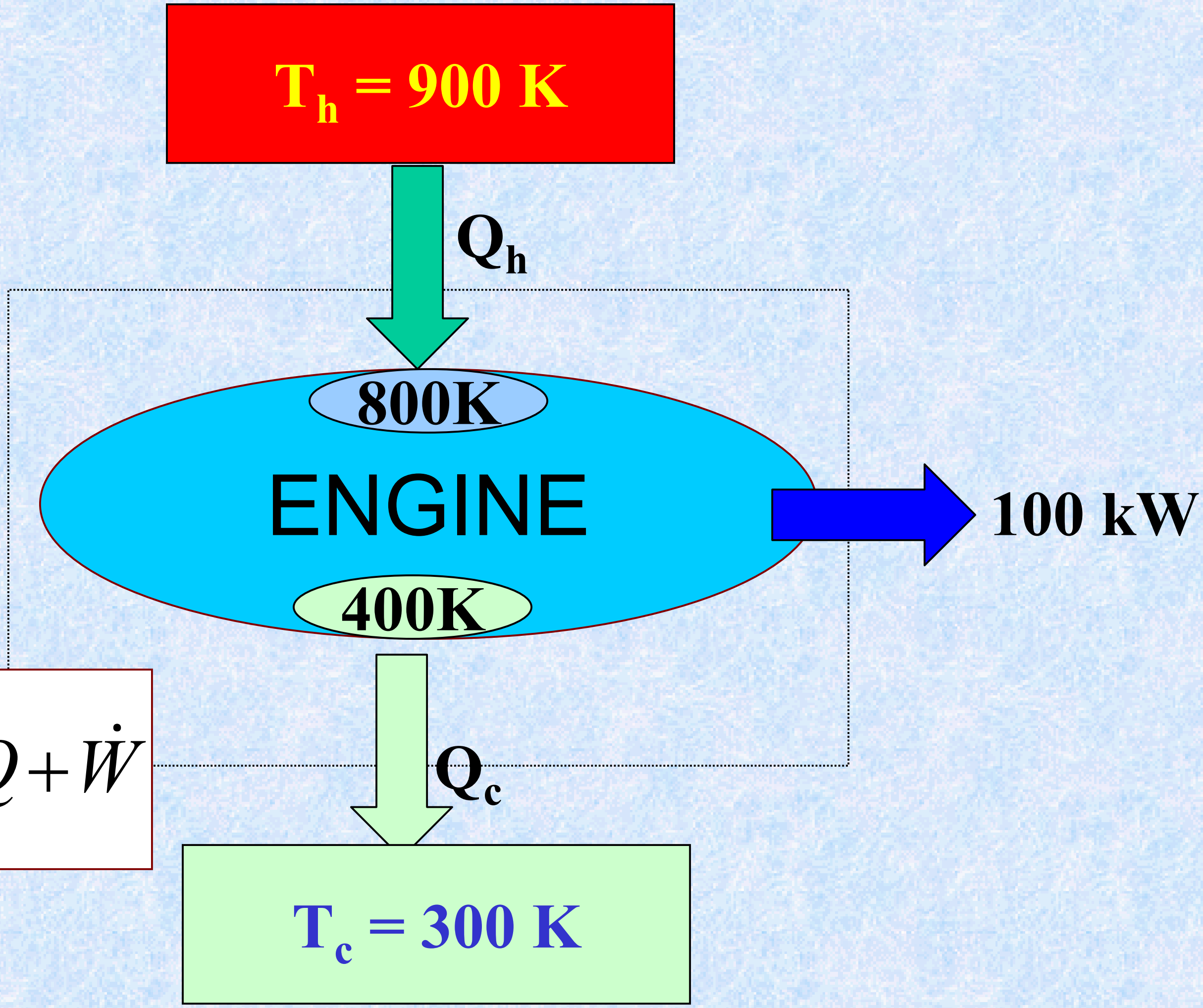


Trend to Equilibrium

Examples of Second Law Analysis

A heat engine operates in a cycle between two thermal reservoirs at 300K and 900K and produces 100kW power. Find the heat rejection and entropy generation when the engine is internally reversible but receives heat and rejects heat at 800K and 400k respectively

First Law in rate terms:



$$\frac{dE}{dt} = \frac{dQ}{dt} + \frac{dW}{dt} = \dot{Q} + \dot{W}$$

For this cycle:

$0 = \Sigma Q - 100$

$Q_h - Q_c = 100$

Since the engine is internally reversible : $Q_h/800 - Q_c/400 = 0$

$Q_h = 200\text{kW}$

$Q_c = 100\text{kW}$

Example 1....

Second Law in rate terms:

$$\frac{dS}{dt} = \sum \frac{\dot{Q}}{T} + \frac{d\sigma}{dt}$$

For this cycle :

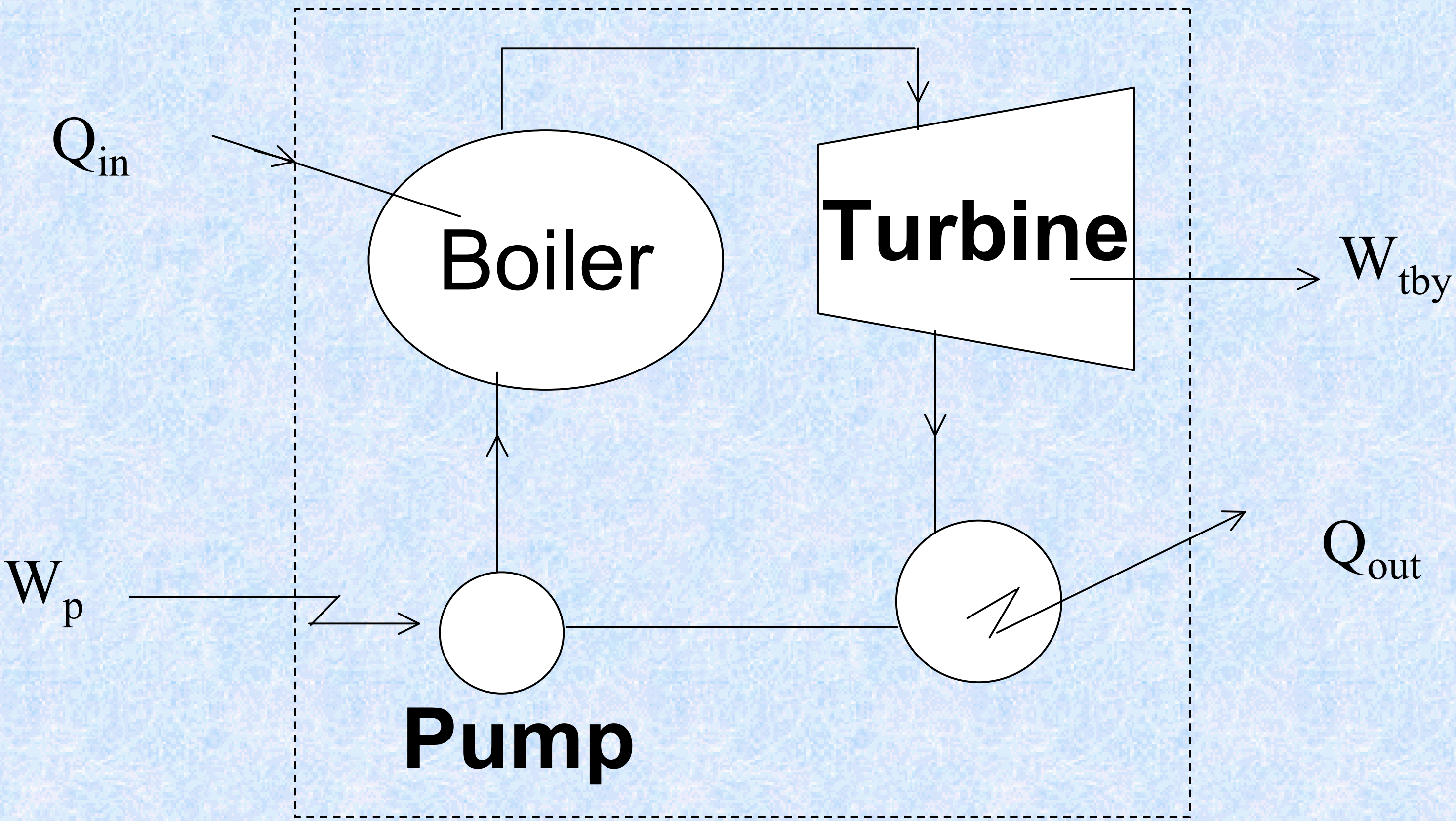
$$\frac{d\sigma}{dt} = -\langle \frac{Q_h}{900} - \frac{Q_C}{300} \rangle$$

This gives entropy generation rate as:
-[200/900 - 100/300] = 0.111 kW / K

EXAMPLE 2

A simple steam power cycle producing 100 MW of power receives heat at 900K in the boiler and rejects heat at 320K. The condensate pump consumes 50kW of power, and the boiler consumes 54 tonnes/hour of coal. Assuming that the combustion of 1Kg of coal releases 20MJ of heat determine the thermal efficiency and entropy generation in the cycle.

EXAMPLE 2……



EXAMPLE 2 ....

First Law (for System within dashed line boundaries)

$$\frac{dE}{dt} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{P_{in}} - \dot{W}_{T,by}$$

Under steady state conditions, $\frac{dE}{dt} = 0$

$$\Rightarrow \dot{Q}_{in} - \dot{Q}_{out} = \dot{W}_{T,by} - \dot{W}_{P_{in}}$$

Here

$$\dot{Q}_{in} = \frac{54 \times 1000}{3600} \times 20\, MJ/S$$

$$= 300 MW$$

$$\dot{Q}_{out} = 300 - 100$$

$$= 200\ MW$$

EXAMPLE 2 ……………

Second Law (for system within dashed line boundaries)

$$\frac{dS}{dt} = \sum \frac{\dot{Q}}{T} + \dot{\sigma}$$

Under steady state conditions, $\frac{dS}{dt} = 0$

$$\Rightarrow \dot{\sigma} = -\sum\left(\frac{\dot{Q}}{T}\right)$$

Here

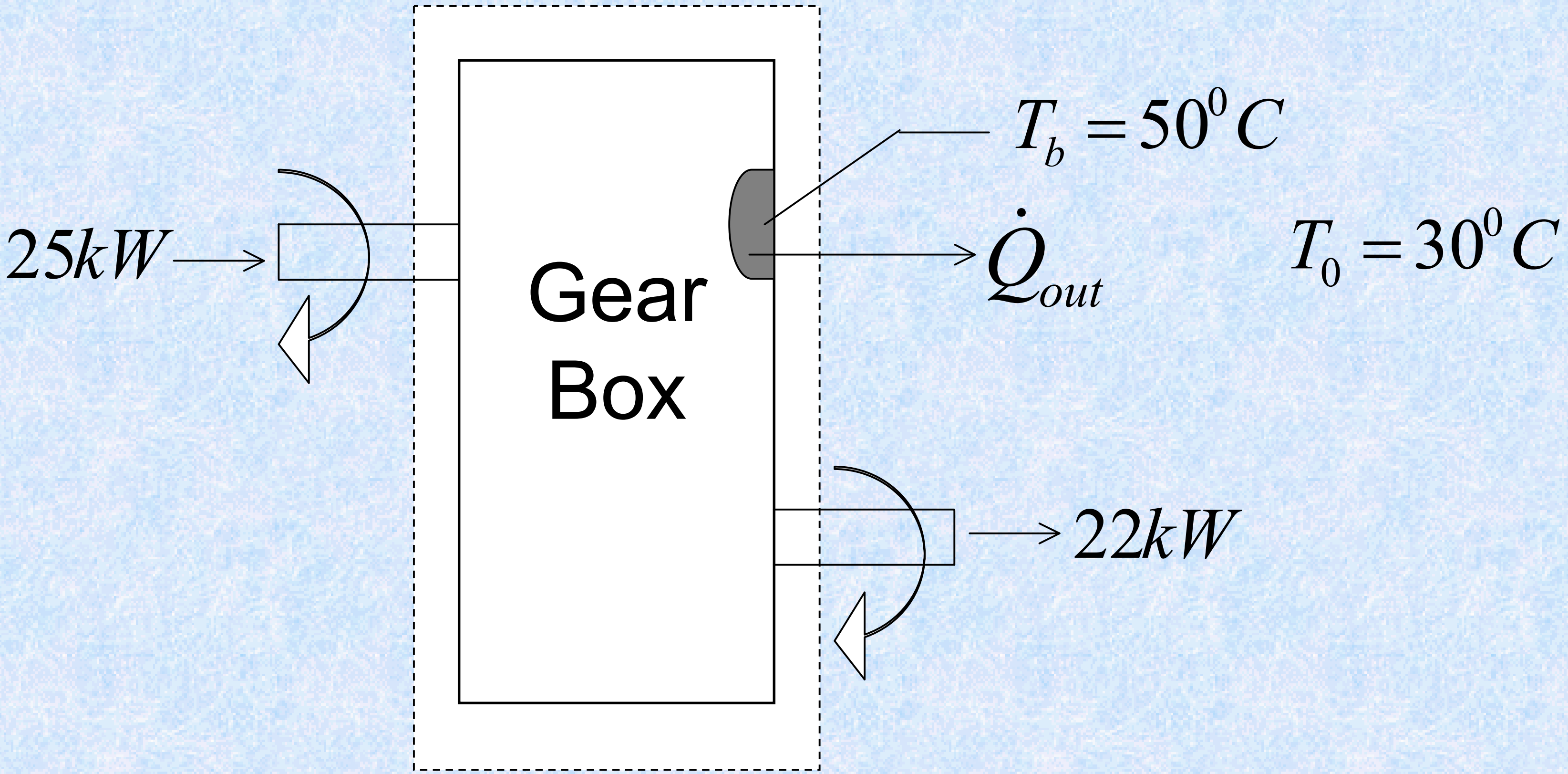
$$\dot{\sigma} = -\left(\frac{300}{900} - \frac{200}{320}\right)\frac{MW}{K}$$

$$= .2917 MW/K$$

EXAMPLE 3

The gear box of a machine is operating under steady-state conditions. The input shaft receives 25 kW from a prime mover and transmits 22kW to the output shaft, the rest being lost due to friction etc. The gear box surface is at an average temperature of 50^0C and loses heat to the surroundings at 30^0C. Estimate the rate of entropy production inside the gear box.

EXAMPLE 3



EXAMPLE 3

Since the gear box is operating in steady state,

First Law $$0 = 25 - 22 - \dot{Q}_{out} \Rightarrow \dot{Q}_{out} = 3KW$$

Second Law $$\dot{\sigma} = -\sum\left(\frac{\dot{Q}}{T}\right) = \frac{\dot{Q}_{out}}{T} = \frac{3\times1000}{323} = 9.289\ W/K$$

Entropy production outside the box?

End of Lecture

Lecture 2.9

The Second Law …..Corollaries & Applications

ENTROPY MAX PRINCIPLE

for any process

$$dS \geq \frac{dQ}{T} \Rightarrow dS = \frac{dQ}{T} + d\sigma$$

$$where \quad d\sigma \geq 0$$ ≡ **entropy gen.**

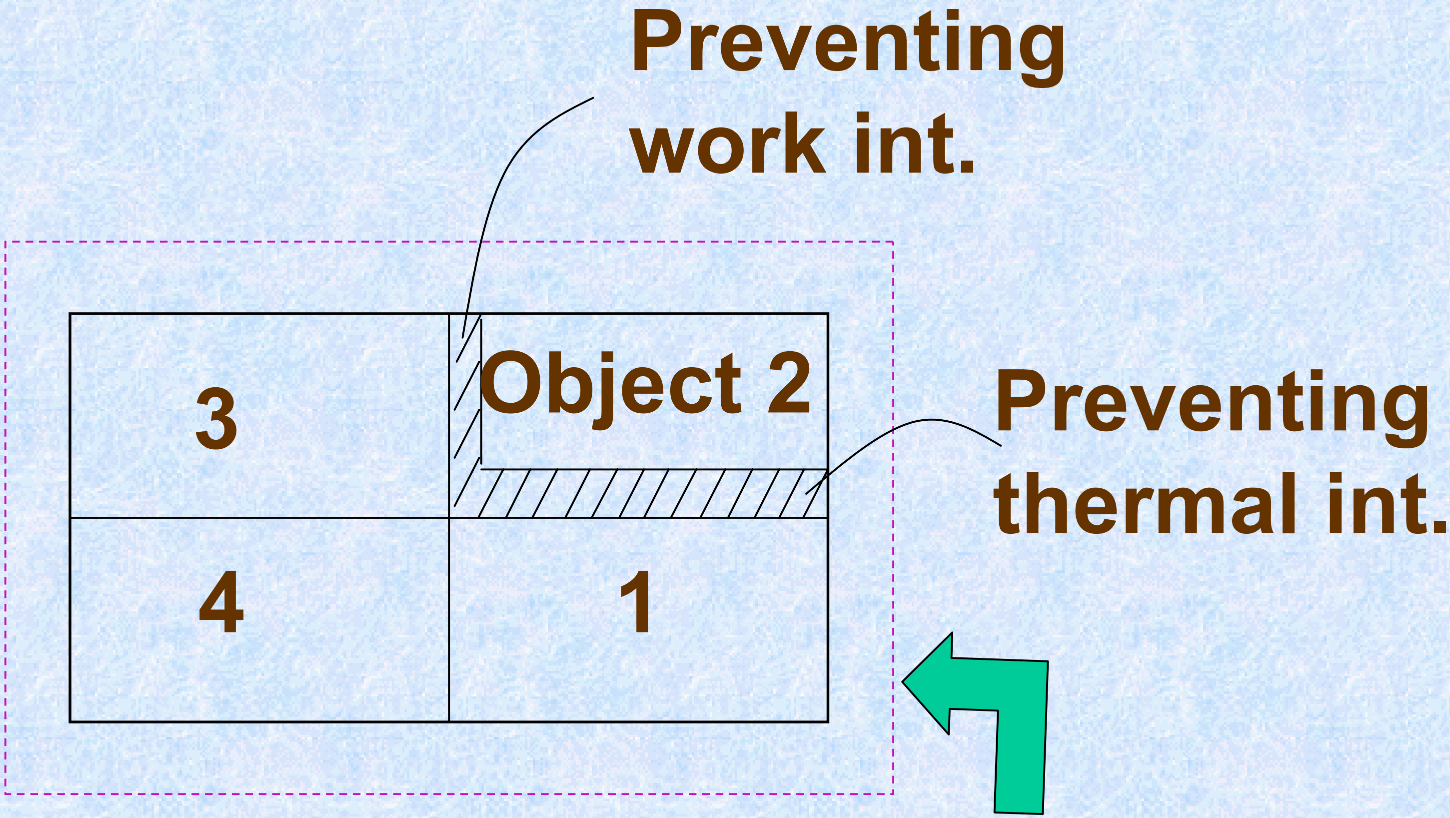
In rate terms: $\frac{dS}{dt} = \frac{\dot{Q}}{T} + \frac{d\sigma}{dt} = \frac{\dot{Q}}{T} + \dot{\sigma}$

In the absence of thermal interaction

$$ds = d\sigma \geq 0$$

Principle of Increase of entropy

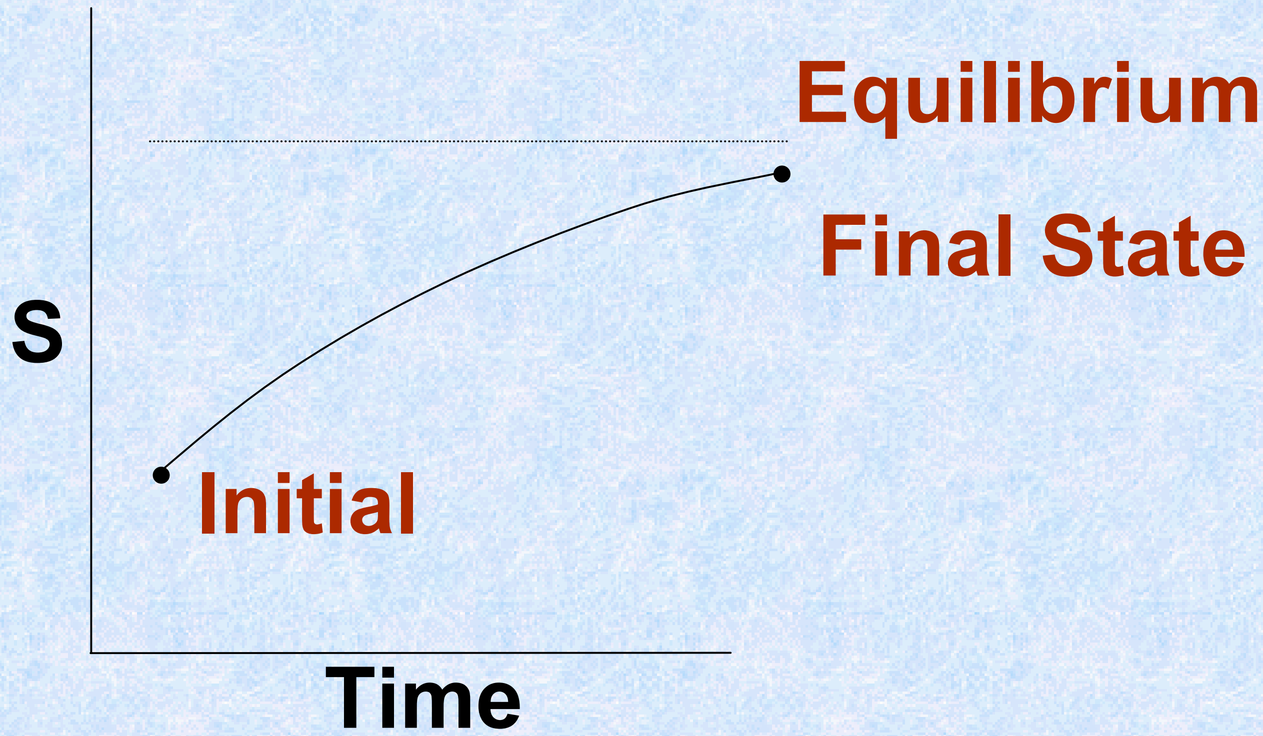
ENTROPY MAX PRINCIPLE



Composite system is isolated

The entropy reaches maximum possible value at the equilibrium

ENTROPY MAX PRINCIPLE



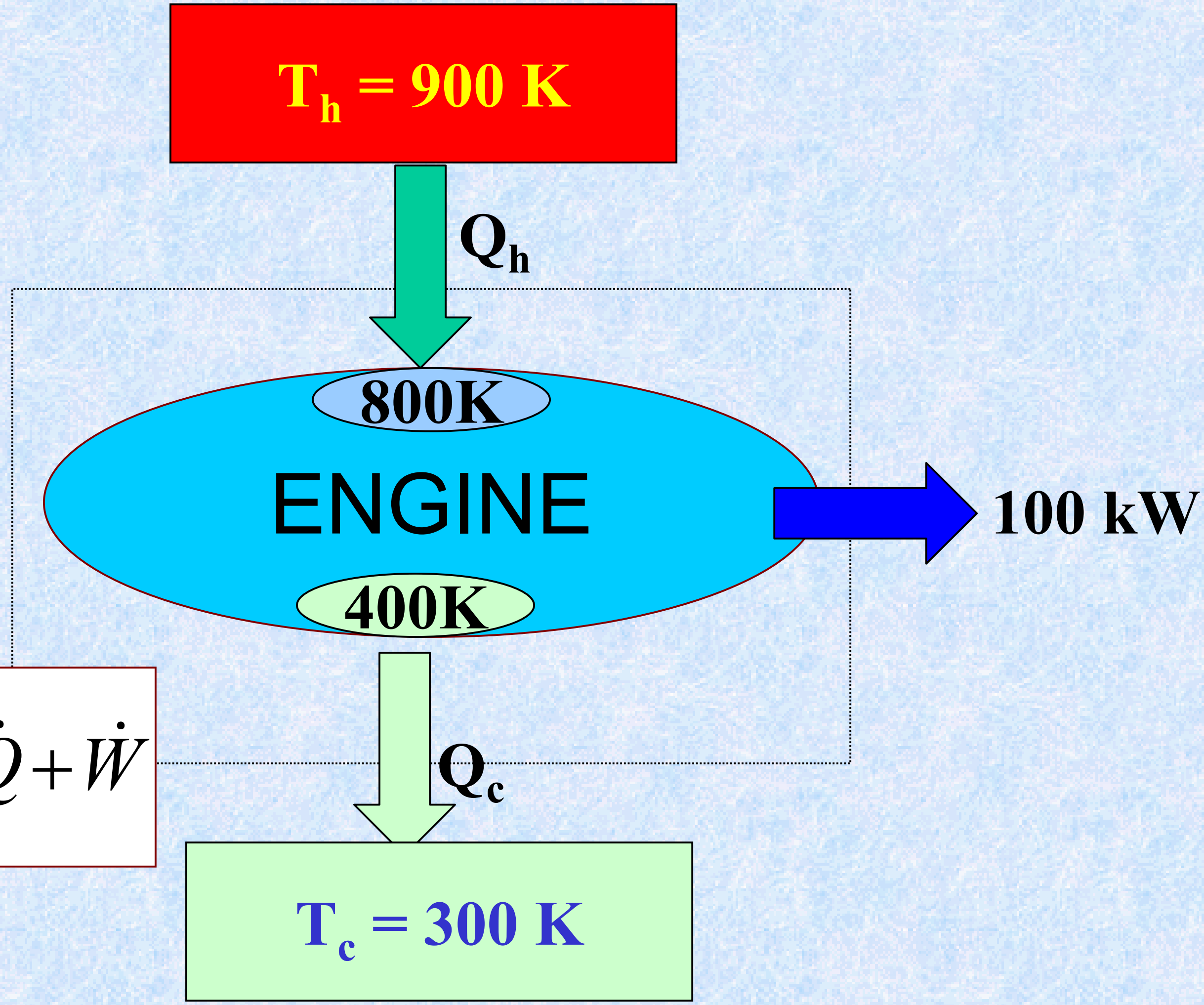
Trend to Equilibrium

Examples of Second Law Analysis

A heat engine operates in a cycle between two thermal reservoirs at 300K and 900K and produces 100kW power. Find the heat rejection and entropy generation when the engine is internally reversible but receives heat and rejects heat at 800K and 400k respectively

First Law in rate terms:

$$\frac{dE}{dt} = \frac{dQ}{dt} + \frac{dW}{dt} = \dot{Q} + \dot{W}$$



For this cycle:

$0 = \Sigma Q - 100$

$Q_h - Q_c = 100$

Since the engine is internally reversible : $Q_h/800 - Q_c/400 = 0$

$Q_h = 200\text{kW}$

$Q_c = 100\text{kW}$

Example 1….

Second Law in rate terms:

$$\frac{dS}{dt} = \sum \frac{\dot{Q}}{T} + \frac{d\sigma}{dt}$$

For this cycle :

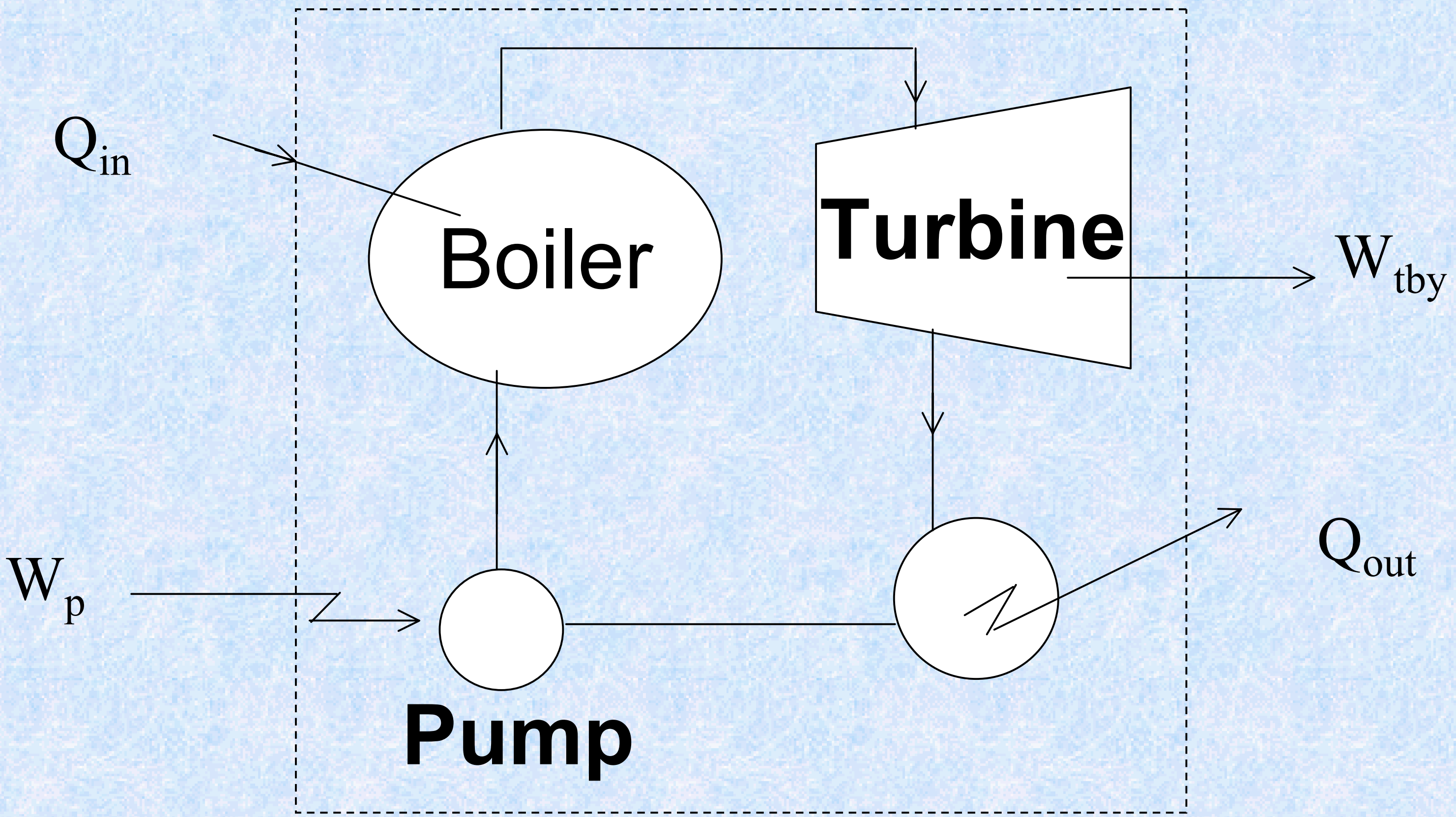
$$\frac{d\sigma}{dt} = -\left\langle \frac{Q_h}{900} - \frac{Q_C}{300} \right\rangle$$

This gives entropy generation rate as:
-[200/900 - 100/300] = 0.111 kW / K

EXAMPLE 2

A simple steam power cycle producing 100 MW of power receives heat at 900K in the boiler and rejects heat at 320K. The condensate pump consumes 50kW of power, and the boiler consumes 54 tonnes/hour of coal. Assuming that the combustion of 1Kg of coal releases 20MJ of heat determine the thermal efficiency and entropy generation in the cycle.

EXAMPLE 2……



EXAMPLE 2 …………..

First Law (for System within dashed line boundaries)

$$\frac{dE}{dt} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{\mathrm{P}_{in}} - \dot{W}_{T,by}$$

Under steady state conditions, $\frac{dE}{dt} = 0$

$$\Rightarrow \dot{Q}_{in} - \dot{Q}_{out} = \dot{W}_{T,by} - \dot{W}_{\mathrm{P}_{in}}$$

Here

$$\dot{Q}_{in} = \frac{54 \times 1000}{3600} \times 20\, MJ/S$$

$$= 300 MW$$

$$\dot{Q}_{out} = 300 - 100$$

$$= 200\ MW$$

EXAMPLE 2 …………..

Second Law (for system within dashed line boundaries)

$$\frac{dS}{dt} = \Sigma \frac{\dot{Q}}{T} + \dot{\sigma}$$

Under steady state conditions, $\frac{dS}{dt} = 0$

$$\Rightarrow \dot{\sigma} = -\Sigma\left(\frac{\dot{Q}}{T}\right)$$

Here

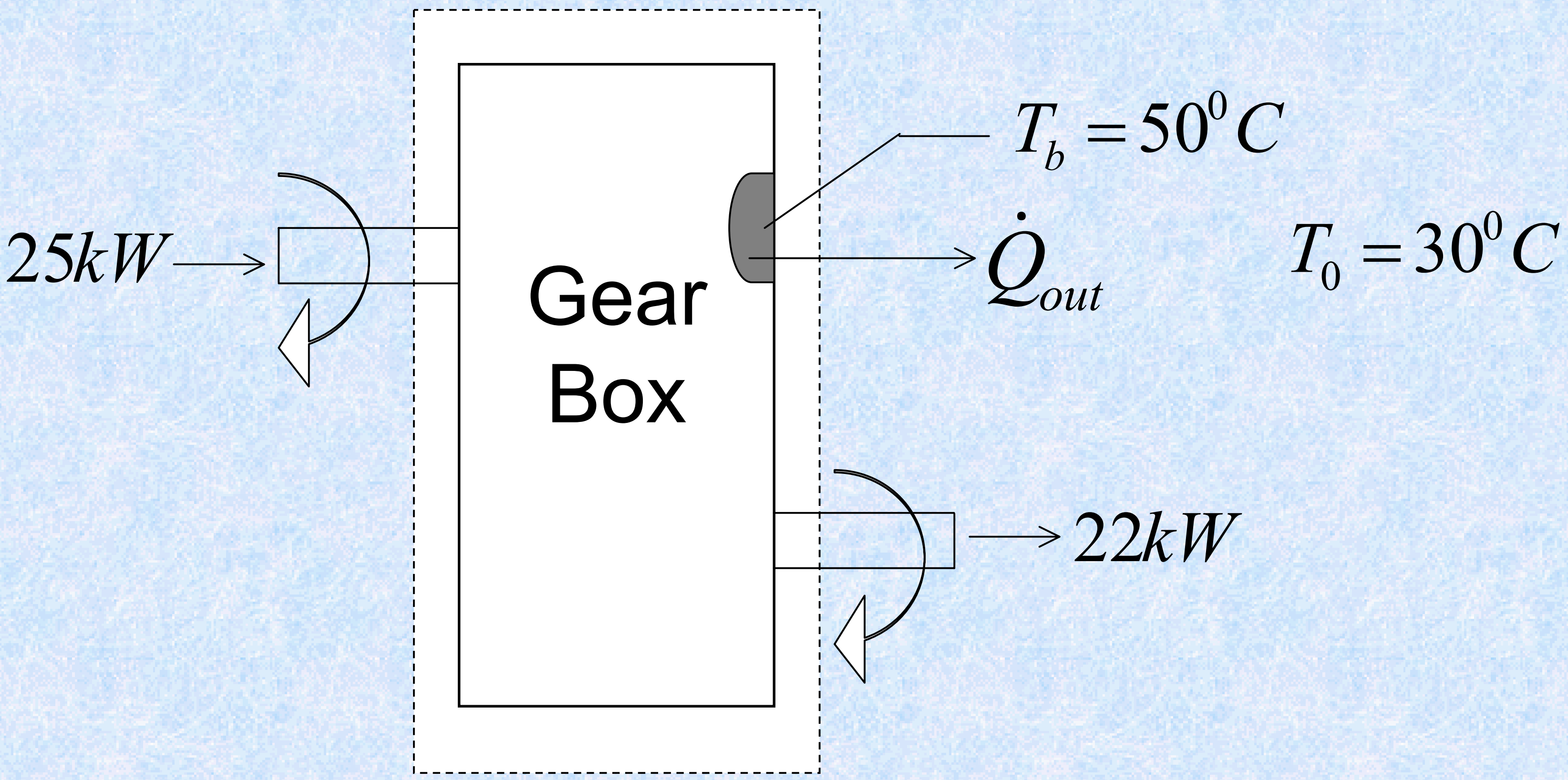
$$\dot{\sigma} = -\left(\frac{300}{900} - \frac{200}{320}\right)\frac{MW}{K}$$

$$= .2917 MW/K$$

EXAMPLE 3

The gear box of a machine is operating under steady-state conditions. The input shaft receives 25 kW from a prime mover and transmits 22kW to the output shaft, the rest being lost due to friction etc. The gear box surface is at an average temperature of 50^0C and loses heat to the surroundings at 30^0C. Estimate the rate of entropy production inside the gear box.

EXAMPLE 3



EXAMPLE 3

Since the gear box is operating in steady state,

First Law $0 = 25 - 22 - \dot{Q}_{out} \Rightarrow \dot{Q}_{out} = 3KW$

Second Law $\dot{\sigma} = -\sum\left(\frac{\dot{Q}}{T}\right) = \frac{\dot{Q}_{out}}{T} = \frac{3\times1000}{323} = 9.289\ W/K$

Entropy production outside the box?

End of Lecture