Reversible processes :

If you recall from the last lecture, all processes in nature occur in a certain direction. These processes cannot be reversed.

Reversible processes are those in which both the system and the surroundings can be restored to original states by performing the process in reverse directions.

Reversible processes are idealizations of the actual (irreversible) processes

Why should we care about reversible processes ?

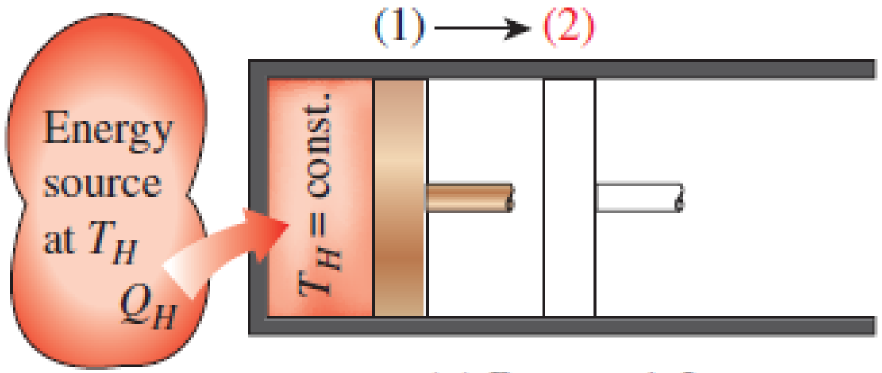
This is because the work producing devices such as heat engines, turbines perform the maximum work if the process is reversible

On the other hand, work consuming devices such as pumps and compressors use the least work when the processes are reversible.

Carnot cycle :

An ideal cycle consisting of four reversible processes. Below we describe each process. Working fluid is a gas enclosed in a piston-cylinder arrangement.

(a) Reversible isothermal expansion :



(*a*) Process 1-2

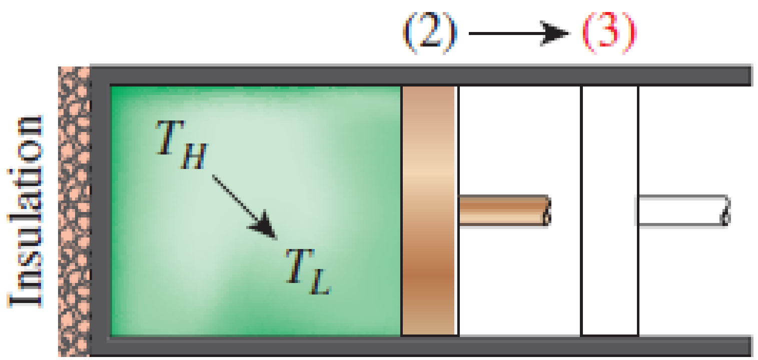
Gas expands as a result of heat transfer. There is no friction in the entire assembly

Temperature of the gas is lower by an infinitesimal amount dT. Thus, Temperature of the gas = $(T_H - dT) = T_H$ (in the limit as $dT \rightarrow 0$)

Also, $P_{ext} = (P - dP) = P$ in the limit as $dP \rightarrow 0$ (infinitesimal pressure difference)

Carnot cycle :

(b) Reversible adiabatic expansion :



(*b*) Process 2-3

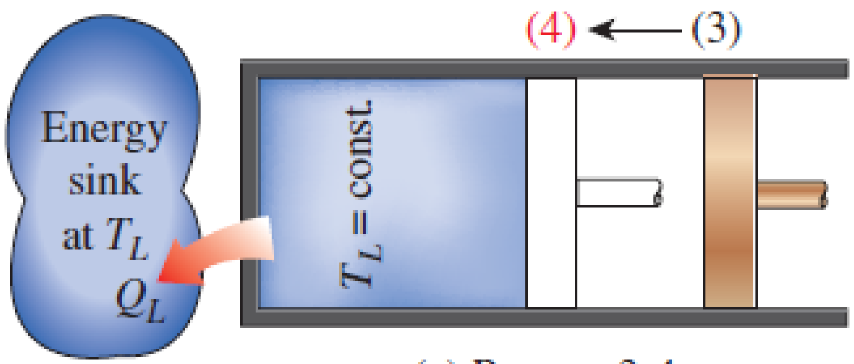
Entire piston-cylinder assembly is insulated.   There is no friction in the entire assembly

Also, P_{ext} = (P – dP) = P in the limit as dP →0 (infinitesimal pressure difference)

Thus gas expands reversibly and adiabatically.   Gas temperature drops from T_H to T_L

Carnot cycle :

(c) Reversible isothermal compression :



(c) Process 3-4

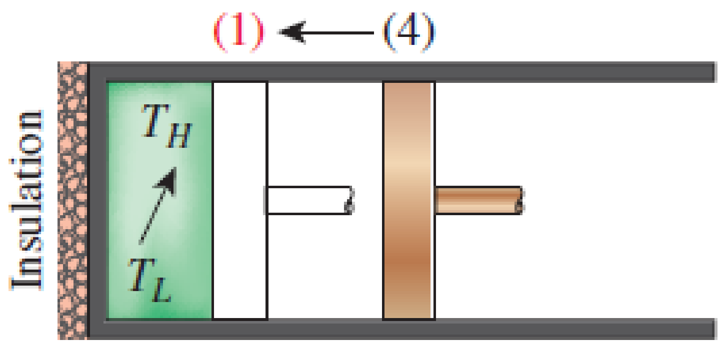
Gas is compressed and there is a heat transfer from the gas to the sink at T_L. There is no friction in the entire assembly.

Temperature of the gas is higher by an infinitesimal amount dT. Thus, Temperature of the gas = $(T_L + dT) = T_L$ (in the limit as $dT \rightarrow 0$)

Also, $P_{ext} = (P + dP) = P$ in the limit as $dP \rightarrow 0$ (infinitesimal pressure difference)

Carnot cycle :

(d) Reversible adiabatic compression :



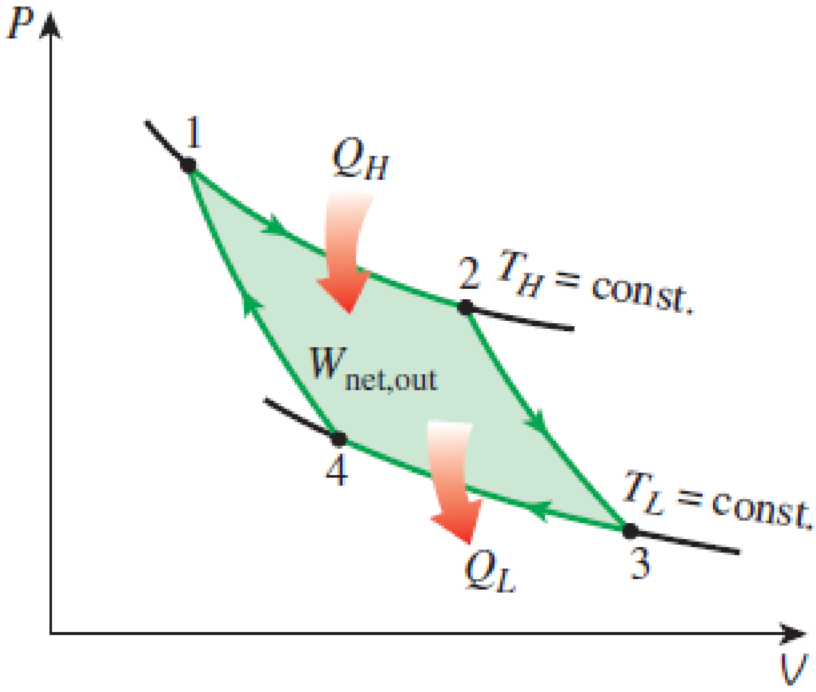
(d) Process 4-1

Gas is compressed while the entire piston-cylinder arrangement is insulated. There is no friction in the entire assembly.

Also, P_{ext} = (P + dP) = P in the limit as dP $\rightarrow$0 (infinitesimal pressure difference)

Thus gas is compressed reversibly and adiabatically. Gas temperature increases from T_L to T_H

Carnot cycle :



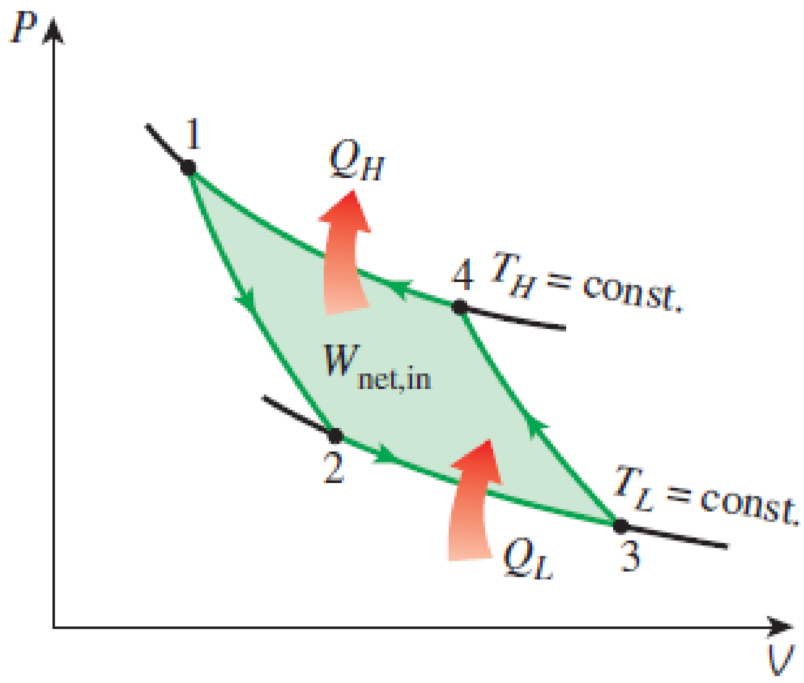
Pressure (P) – Volume (V) diagram for the Carnot cycle is shown above.

Net work done is equal to the shaded area (see figure)

In one cycle there is no change in internal energy of gas since it returns to the original state. Thus, ΔU (one cycle) = $Q_H - Q_L - W_{net,out} = 0$

Therefore, $W_{net,out} = Q_H - Q_L$

Reversed Carnot cycle :



Pressure (P) – Volume (V) diagram for the Reversed Carnot cycle is shown above.

Net work done is equal to the shaded area (see figure)

In one cycle there is no change in internal energy of gas since it returns to the original state. Thus, ΔU (one cycle) = $Q_L - Q_H + W_{net,in} = 0$

$$\text{Therefore,} \quad W_{net,in} = Q_H - Q_L$$

Carnot principles (Second law of thermodynamics):

(1) The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

(2) The efficiencies of all reversible heat engines operating between the same two reservoirs is the same.

Both of the above statements are alternate ways of expressing the same general principle of nature which is **Second law of thermodynamics.**

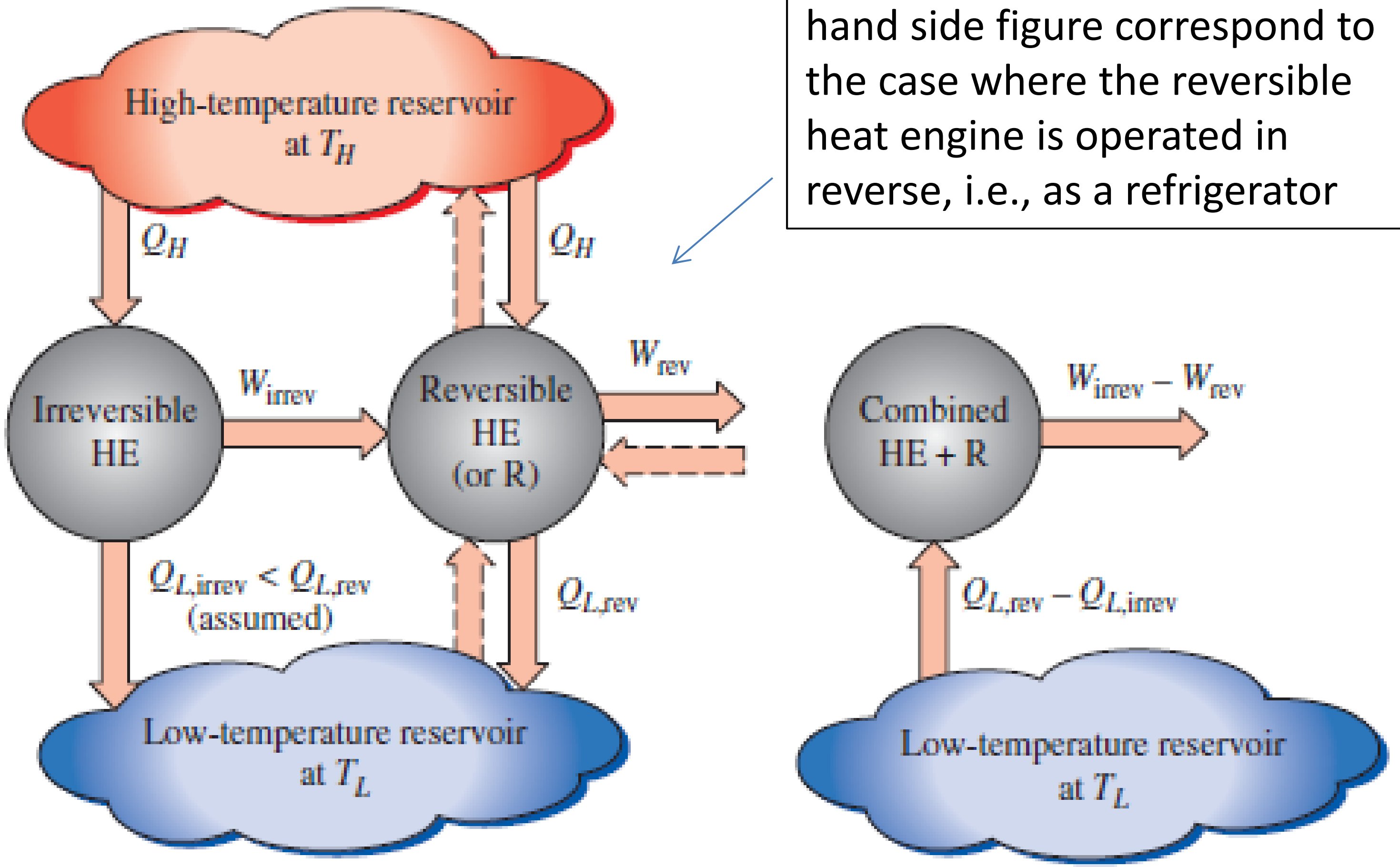
Proof of Carnot principle (1) :

Here (see next slide) we will show that violation of Carnot principle (1) leads to violation of Kelvin—Planck statement

Thus Carnot Principle (1) is equivalent to Kelvin—Planck statement

Proof of Carnot principle (1):

The dashed arrows on the left hand side figure correspond to the case where the reversible heat engine is operated in reverse, i.e., as a refrigerator



(*a*) A reversible and an irreversible heat engine operating between the same two reservoirs (the reversible heat engine is then reversed to run as a refrigerator)

(*b*) The equivalent combined system

Violation of Carnot Principle (1) [see Fig. (a)] leads to violation of Kelvin—Planck statement [see Fig. (b)]

Thermodynamic temperature scale :

Recall that in the early part of the course, we had discussed Zeroth law of thermodynamics and how it enables us to measure temperature.

Celcius and Farenheit scales are empirical scales. The zero of an empirical scale do not have any fundamental basis.

Thermodynamic temperature scales are defined based on the Second law of Thermodynamics .

Thus the zero of this temperature scale
is not based on the state of any particular substance.

Thermodynamic temperature scale :

Based on Second law of thermodynamics it will be shown that the ratio of heat absorbed (Q_H) and heat rejected (Q_L) by a reversible heat engine is given by

$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$$

where T_H and T_L are the temperatures of the high temperature and low temperature reservoirs defined according to **Thermodynamic temperature scale** (this scale is also known as Kelvin scale in SI units).

Thermal efficiency of a Carnot heat engine :

Based on the relation of heats absorbed and heat rejected As given in the last slide, the thermal efficiency of a Carnot heat engine is given by,

$$\eta_{th,rev} = \left(1 - \frac{Q_L}{Q_H} \right)$$

$$= \left(1 - \frac{T_L}{T_H} \right)$$

According to Carnot Principle (1), the efficiency of a irreversible heat engine will always be less than the efficiency of a reversible heat engine operating between the same two reservoirs.

Carnot refrigerator and Carnot Heat Pump :

Recall that the coefficients of performance of refrigerator And heat pump are given by

$$\mathrm{COP}_{\mathrm{R}} = \frac{1}{Q_H/Q_L - 1} \quad \text{and} \quad \mathrm{COP}_{\mathrm{HP}} = \frac{1}{1 - Q_L/Q_H}$$

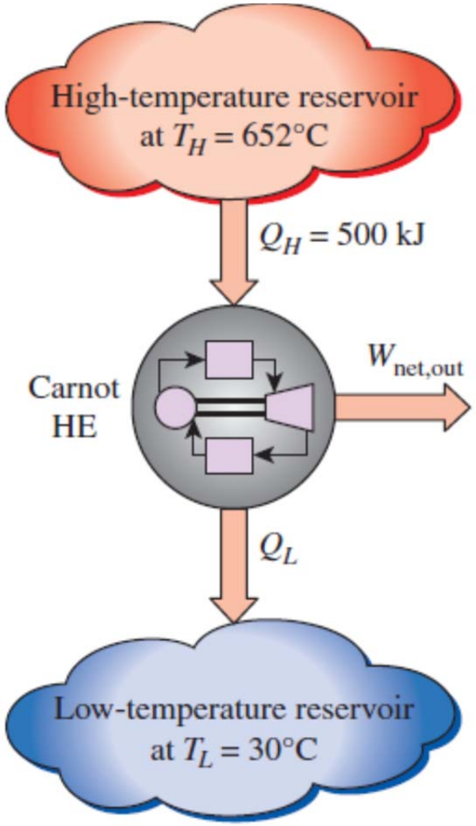
Based on the thermodynamic temperature scale, we get the following expression for Carnot refrigerator and Carnot Heat Pump which operate on reversible cycles :

$$\mathrm{COP}_{\mathrm{R,rev}} = \frac{1}{T_H/T_L - 1}$$

$$\mathrm{COP}_{\mathrm{HP,rev}} = \frac{1}{1 - T_L/T_H}$$

Carnot heat engine : Example

A Carnot heat engine, shown in Fig. receives 500 kJ of heat per cycle from a high-temperature source at 652°C and rejects heat to a low-temperature sink at 30°C. Determine (*a*) the thermal efficiency of this Carnot engine and (*b*) the amount of heat rejected to the sink per cycle.



Answers :

$$\eta_{th,rev} = 0.672$$

$$Q_{L,rev} = 164 \text{ kJ}$$