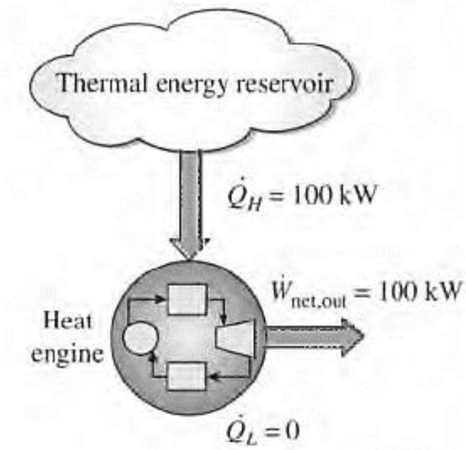
EX) A car engine with output power of 65 hp and has a thermal efficiency of 35 percent. Determine the fuel (ρ = 720 Kg/s) consumption rate (L/h) of the car if the fuel has a heating value of 46 MJ/Kg.

**Kelvin-Planck Statement of 2nd Law**

Even under ideal conditions, a heat engine must reject some heat to a low-temperature reservoir in order to complete the cycle. That is, no heat engine can convert all the received heat to useful work.

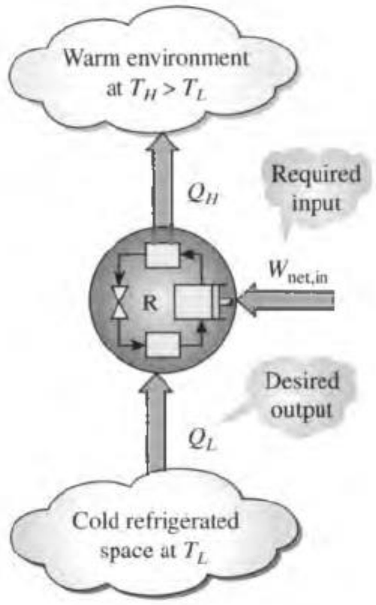
It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.




**Refrigeration**

Naturally, heat is transferred from high-temperature mediums to low-temperature ones. However, the reverse process, cannot occur by itself. That is transferring heat from a low-temperature medium to a high-temperature one requires special device called Refrigerator.

Refrigerators, like heat engines, are cyclic devices. The working fluid used in the refrigeration cycle is called a refrigerant. Refrigerators involves four main components: a compressor, a condenser, an expansion valve and an evaporator as shown below:



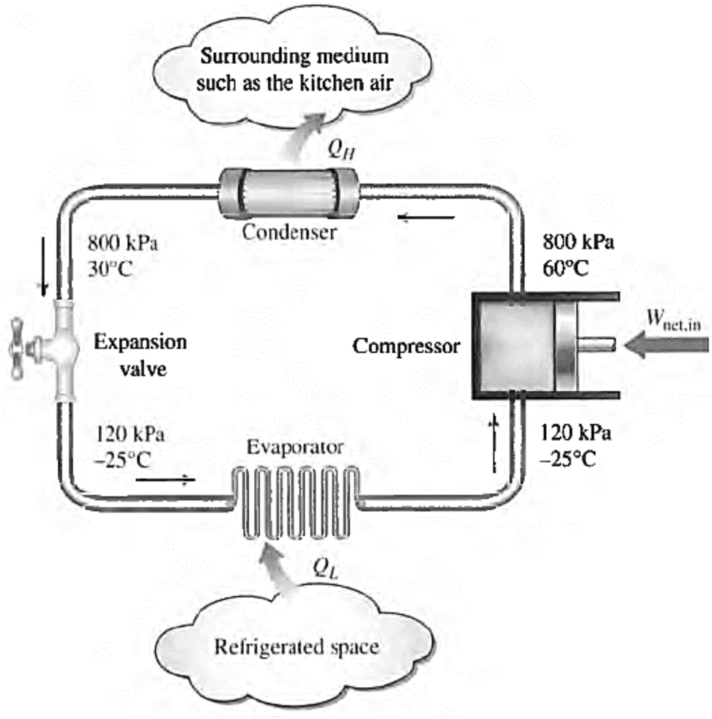
**How compressor Works?**

The refrigerant enters the compressor as a vapor and is compressed to higher pressure.

It leaves the compressor at a relatively high temperature and cools down and condenses as it flows through the coils of the condenser by rejecting heat to the surrounding medium.

It then enters a capillary tube where its pressure and temperature drop drastically due to the throttling effect.

The low-temperature refrigerant then enters the evaporator, where it evaporates by absorbing heat from the refrigerated space.




## Coefficient of Performance

The ***efficiency*** of a refrigerator is expressed in terms of the **coefficient of performance** (COP).

$$COP = \frac{Q_L}{W_{in}}$$

$$W_{in} = Q_H - Q_L$$

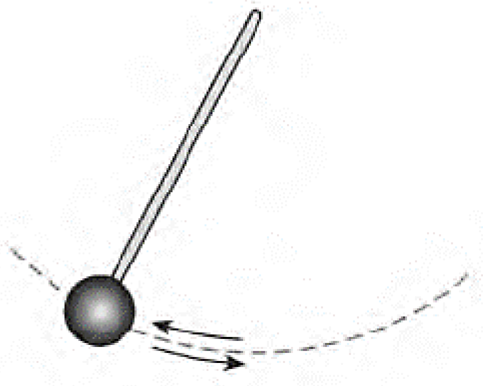
$$COP = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

Notice that the value of COPR can be ***greater than unity.*** That is, the amount of heat removed from the refrigerated space can be greater than the amount of work input. This is in contrast to the thermal efficiency, which can never be greater than one.

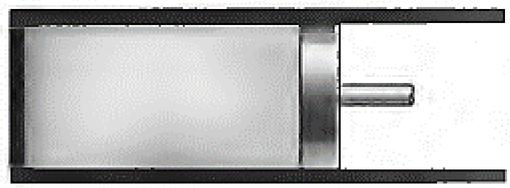
**Ex)** Heat is removed from the food compartment of a refrigerator at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, determine (a) the coefficient of performance of the refrigerator and (b) the rate of heat rejection to the room that houses the refrigerator.

## Reversible and Irreversible Processes

**Reversible process** is an idealized process. It is defined as a process that can be reversed without leaving any trace on the surroundings. That is, both the system and the surroundings are returned to their initial states at the end of the process.



(*a*) Frictionless pendulum



(*b*) Quasi-equilibrium expansion and compression of a gas

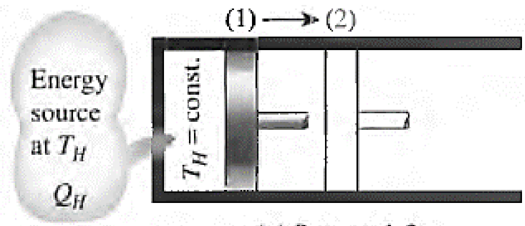
However, all the processes occurring in nature are irreversible. But, we study reversible process because they can be viewed as ***theoretical limits*** for the corresponding irreversible ones.

The factors that cause a process to be irreversible are called **irreversibility**. **Friction** is a familiar form of irreversibility associated with bodies in motion.

## Carnot Cycle

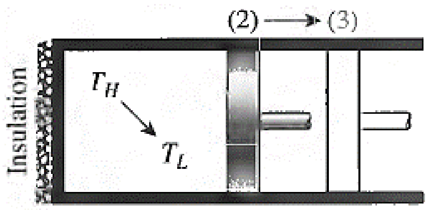
Reversible (theoretical) cycles that provide an upper limit to the performance of real cycles. Carnot cycle is composed of four reversible processes:

a. Process 1-2: Reversible Isothermal Expansion



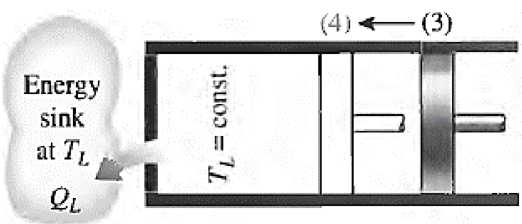

(*a*) Process 1-2

b. Process 2-3: Reversible Adiabatic Expansion



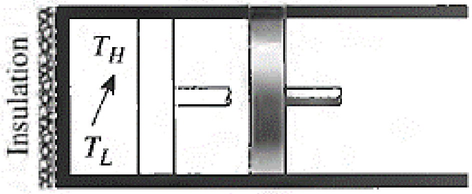

(*b*) Process 2-3

c. Process 3-4: Reversible Isothermal Compression



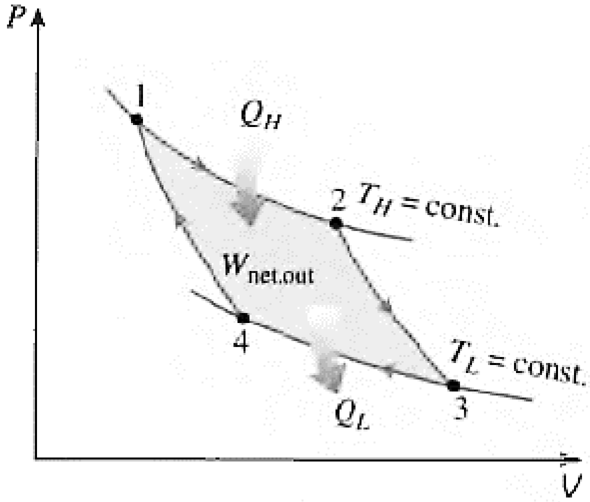

(*c*) Process 3-4

d. Process 4-1: Reversible Adiabatic Compression



(d) Process 4-1

The ***P-W*** diagram of this cycle is shown below:




**Carnot Heat Engine Efficiency**

The efficiency of a heat engine can be found from:

$$\eta = \frac{W_{out}}{Q_H}$$

$$W_{out} = Q_H - Q_L$$

$$\eta = \frac{Q_H - Q_L}{Q_H}$$

$$\eta = 1 - \frac{Q_L}{Q_H}$$

To find $\frac{Q_L}{Q_H}$, consider the four processes shown in the PV diagram above:

**For an Isothermal process**

$$\Delta U = Q - W \text{ , } \Delta U = 0$$

$$Q = W = C \ln\frac{V_2}{V_1} \text{ , } Thus$$

$$\boldsymbol{Process\ 1-2}: Q_H = mRT_H \ \ln\frac{V_2}{V_1} = \ -mRT_H \ \ln\frac{V_1}{V_2}$$

$$\boldsymbol{Process\ 3-4}: Q_L = mR\ T_L \ \ln\frac{V_4}{V_3}$$

$$\frac{Q_L}{Q_H} = \frac{mR\,T_L\,\ln\frac{V_4}{V_3}}{-\,mRT_H\,\ln\frac{V_1}{V_2}} = \frac{T_L\,\ln\frac{V_4}{V_3}}{-T_H\,\ln\frac{V_1}{V_2}} \dots 1$$

**For an adiabatic process**

$$T_1\,V_1^{\gamma-1} = T_2\,V_2^{\gamma-1}$$

**Process 2-3**

$$T_H\,V_2^{\gamma-1} = T_L\,V_3^{\gamma-1} \rightarrow T_H = T_L(\frac{V_3}{V_2})^{\gamma-1}$$

**Process 4-1**

$$T_L\,V_4^{\gamma-1} = T_H\,V_1^{\gamma-1}$$

$$T_L\,V_4^{\gamma-1} = T_L(\frac{V_3}{V_2})^{\gamma-1}\;V_1^{\gamma-1}$$

$$(\frac{V_4}{V_1})^{\gamma-1} = (\frac{V_3}{V_2})^{\gamma-1}$$

$$\left(\frac{V_4}{V_1}\right) = \left(\frac{V_3}{V_2}\right) \rightarrow \left(\frac{V_4}{V_3}\right) = \left(\frac{V_1}{V_2}\right)\ sub.in\ 1$$

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

We know that $Q_L$ is negative since it is Heat Lost, Therefore

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

$$\boxed{\eta_c = 1 - \frac{T_L}{T_H}}$$

Ex) A Carnot heat engine 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 the thermal efficiency of this Carnot engine and the amount of heat rejected to the sink per cycle.