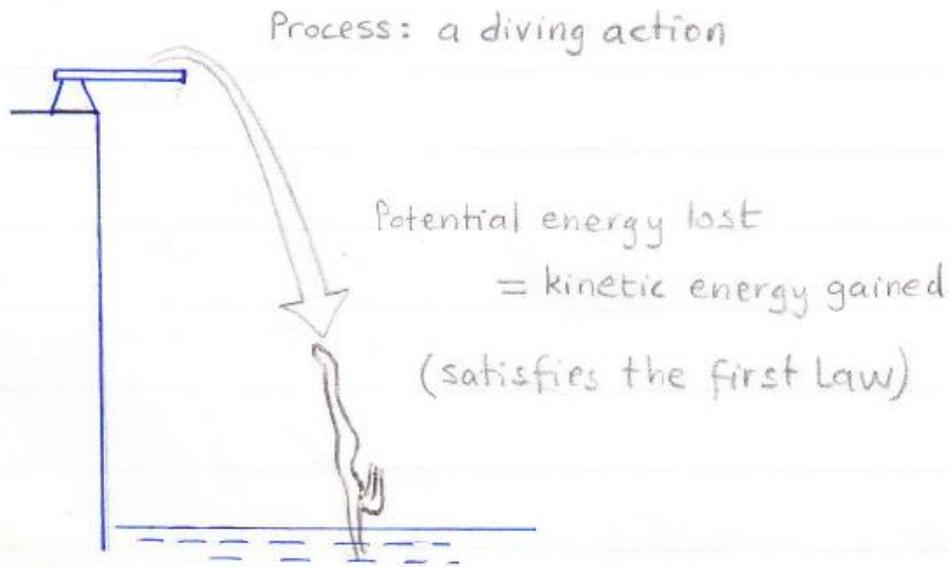


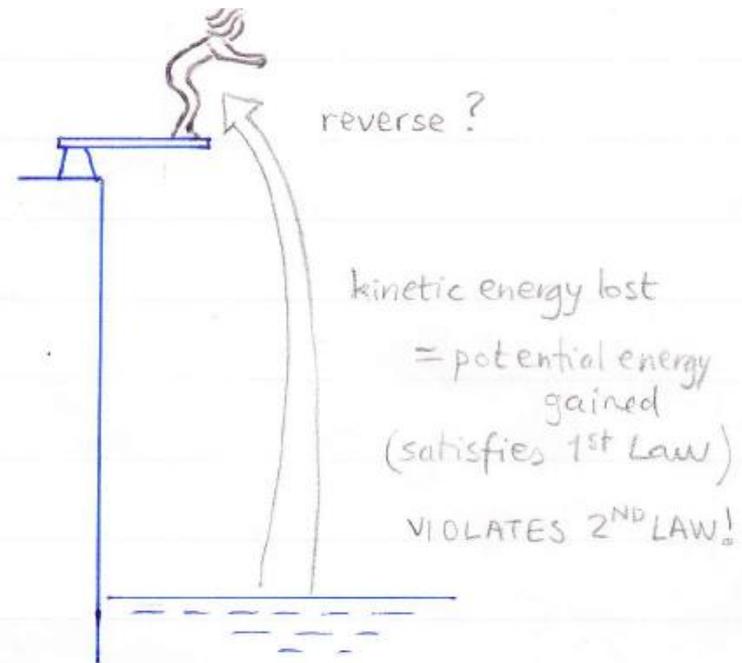
# **The Second Law of Thermodynamics**

→ A process must satisfy the first law to occur

→ However, does it ensure that the process will actually take place?

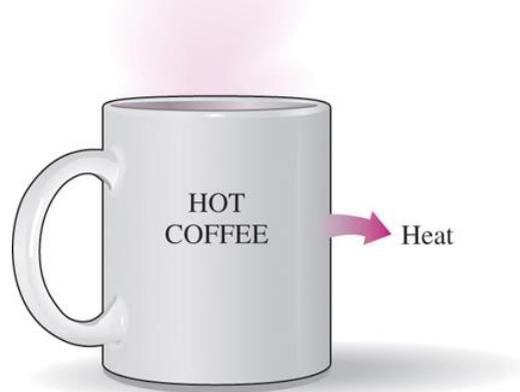


potential energy lost = kinetic energy gained  
(satisfies the first law)

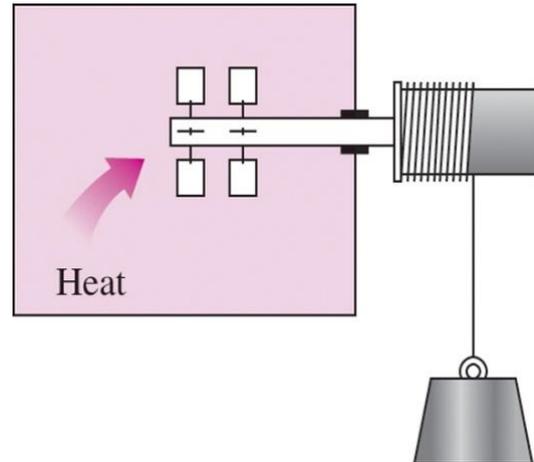


kinetic energy lost = potential energy gained  
(satisfies the first law – VIOLATES the 2nd LAW!)

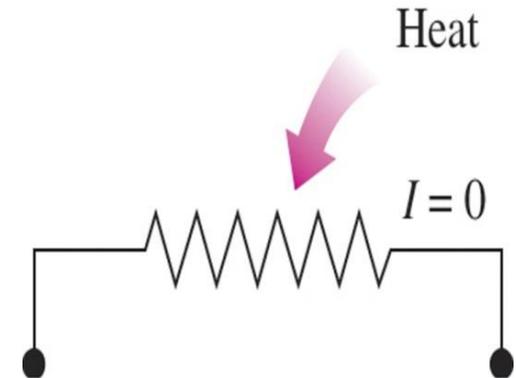
A cup of hot coffee does not get hotter in a cooler room.



Transferring heat to a paddle wheel will not cause it to rotate.



Transferring heat to a wire will not generate electricity.



It is clear from the above examples that processes take place in a certain direction and not in the reverse direction. First law alone is not enough to determine if a process will actually occur.

→ Another principle is needed: **Second law of Thermodynamics**

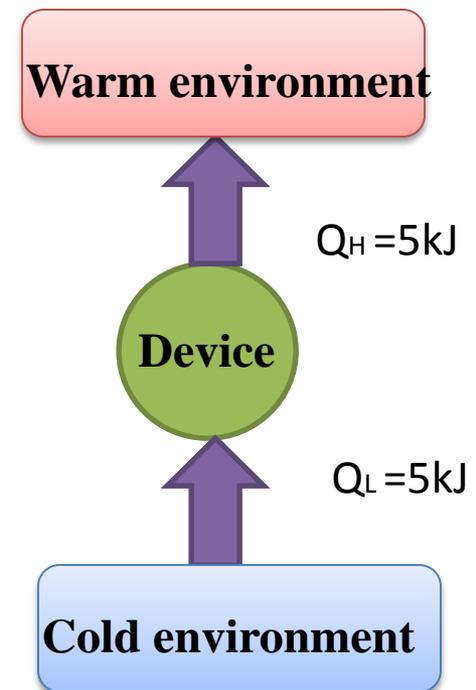
## Second Law is used to:

- Identify the direction of processes
- Determine the quality of energy
- Determine the degree of degradation of energy
- Determine the theoretical limits for the performance of systems

## Clausius statement of the 2<sup>nd</sup> Law:

It is impossible for any device to operate in such a manner that it produces no effect other than the transfer of heat from one body to another body at a higher temperature.

A refrigerator that violates the Clausius statement of the second law.

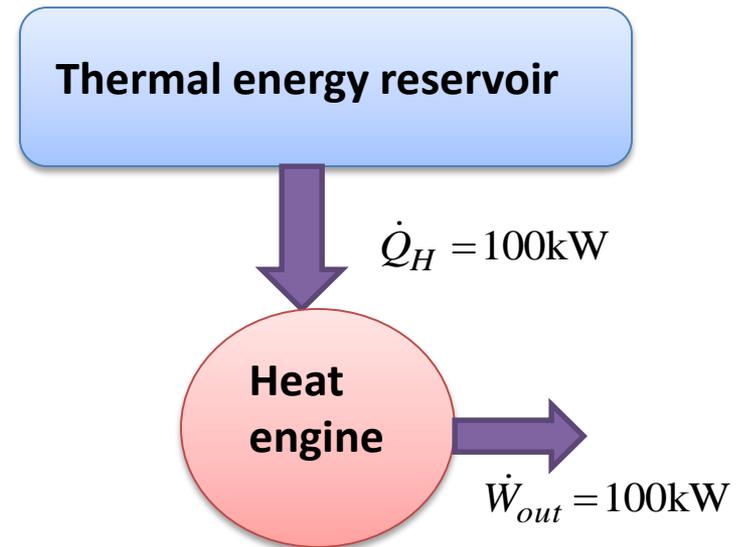


## Kelvin-Plank statement of the 2<sup>nd</sup> Law:

It is impossible for any device to operate in a cycle and produce work while exchanging heat only with a single reservoir (i.e. no engine can have 100% efficiency).

**Violates Kelvin-Planck Statement**

**A heat engine that violates the Kelvin-Planck statement of the second law.**



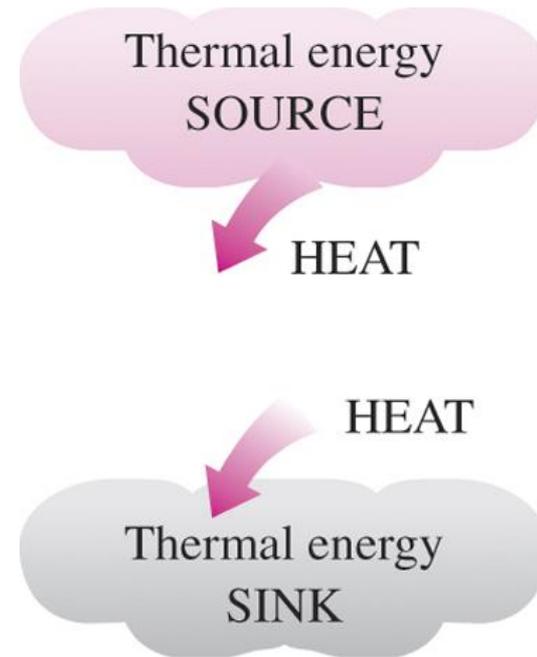
*No heat engine can have a thermal efficiency of 100 percent, or as for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace.*

The impossibility of having a 100% efficient heat engine is not due to friction or other dissipative effects. It is a limitation that applies to both the idealized and the actual heat engines.

## THERMAL ENERGY RESERVOIRS:

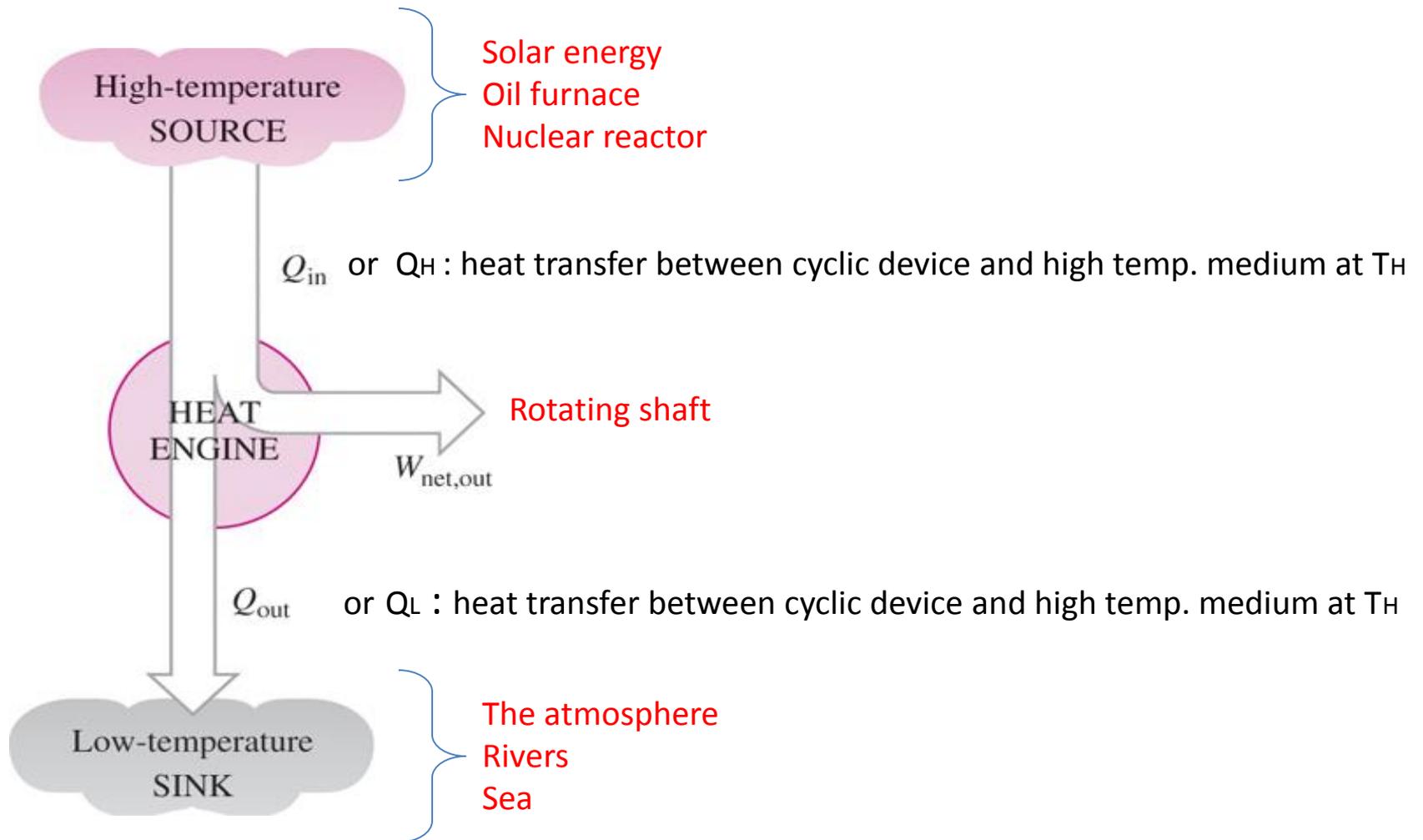
→ Or just a 'reservoir' is defined as a body that can supply or absorb finite amounts of energy as heat without undergoing any change in temperature.

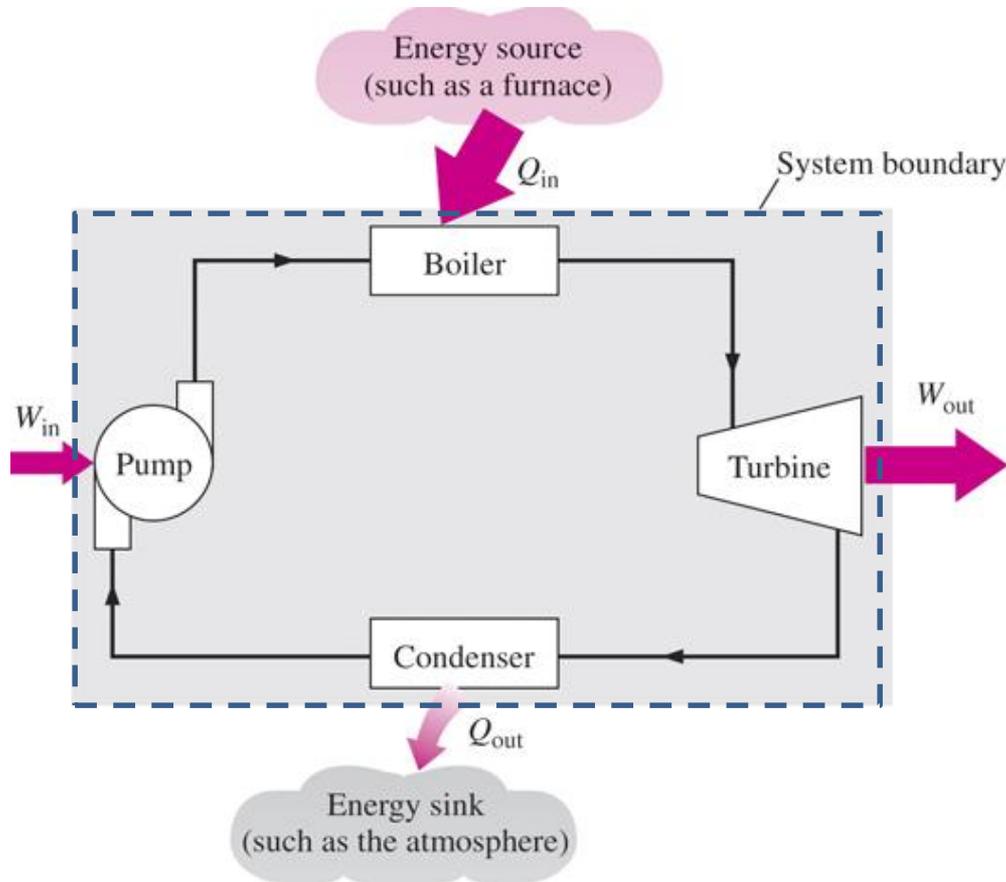
**A source supplies energy in the form of heat, and a sink absorbs it.**



## HEAT ENGINES:

→ are thermodynamic systems operating in a cycle to which net heat is transferred and from which is delivered.





**The work producing device that best fits into the definition of a heat engine is the steam power plant.**

For a closed system undergoing a cycle  $\rightarrow \Delta U=0$

$$W_{\text{net,out}} = W_{\text{out}} - W_{\text{in}} \quad (\text{kJ})$$

$$W_{\text{net,out}} = Q_{\text{in}} - Q_{\text{out}} \quad (\text{kJ})$$

$Q_{\text{in}}$  = amount of heat supplied to steam in boiler from a high-temperature source (furnace)

$Q_{\text{out}}$  = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)

$W_{\text{out}}$  = amount of work delivered by steam as it expands in turbine

$W_{\text{in}}$  = amount of work required to compress water to boiler pressure

## Thermal efficiency

$$\text{In general performance} = \frac{\text{Desired output}}{\text{required input}} = \frac{\text{What I Get}}{\text{What I pay for}}$$

**In heat engines**      **the desired output = net work output** =  $W_{net,out}$

**the required input = heat supplied to system** =  $Q_{in}$

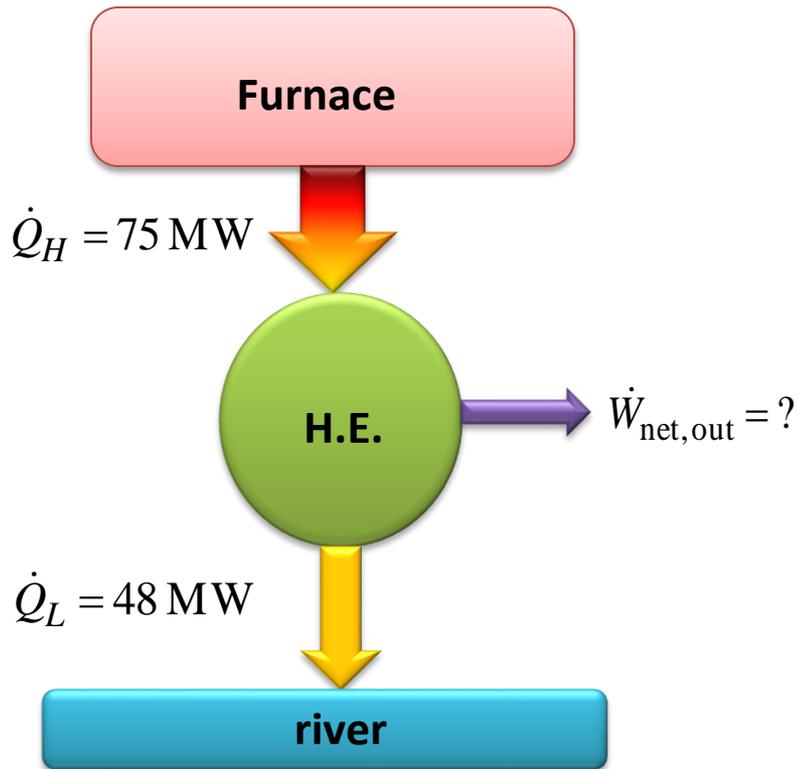
$$\text{Thermal efficiency} \quad \eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$\text{or} \quad \eta_{th} = \frac{W_{net,out}}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

can  $Q_{out} = 0$ ?  $\longrightarrow$  No, because a) the cycle will not be complete!  
b) violates Kelvin-Planck statement.

**Example:**

Heat is transferred to a heat engine from a furnace at a rate of 75MW. If waste heat rejection to a nearby river is 48MW, determine the power output and the thermal efficiency for this heat engine.

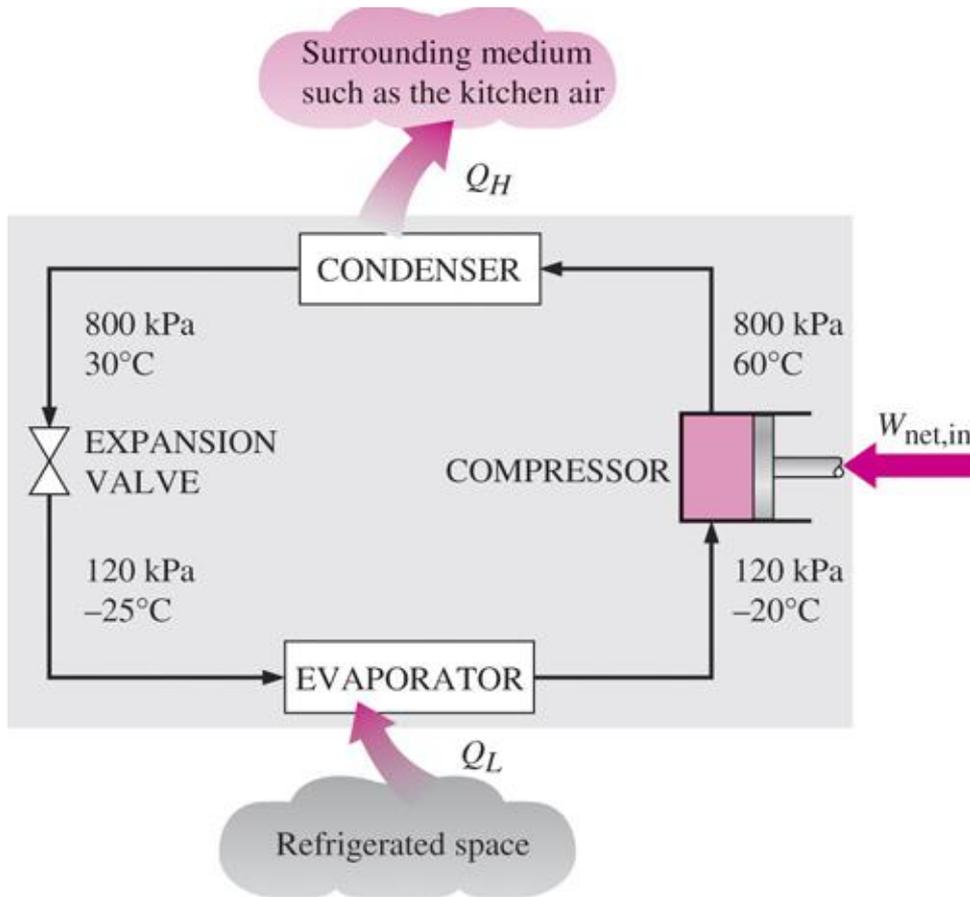


$$\begin{aligned}\dot{W}_{\text{net,out}} &= \dot{Q}_H - \dot{Q}_L \\ &= (75 - 48) \text{ MW} = 27 \text{ MW}\end{aligned}$$

$$\eta_{th} = \frac{W_{\text{net,out}}}{Q_H} = \frac{27 \text{ MW}}{75 \text{ MW}} = 0.36$$

**or 36%**

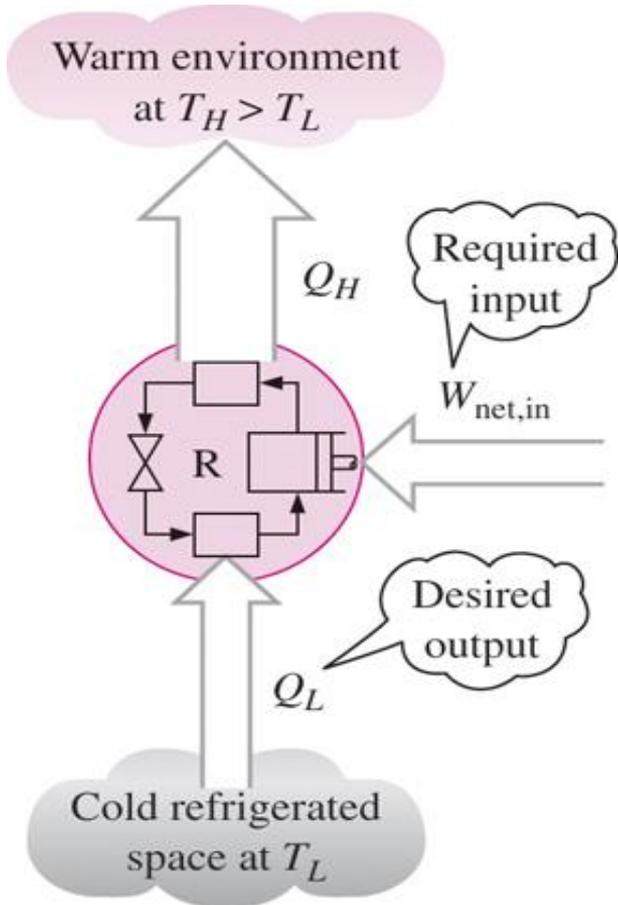
## REFRIGERATORS AND HEAT PUMPS:



- The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called **refrigerators**.
- Refrigerators, like heat engines, are cyclic devices.
- The working fluid used in the refrigeration cycle is called a **refrigerant**.
- The most frequently used refrigeration cycle is the **vapor-compression refrigeration cycle**.

Basic components of a refrigeration system and typical operating conditions.

## Coefficient of Performance:



- The *efficiency* of a refrigerator is expressed in terms of the coefficient of performance (COP).
- The objective of a refrigerator is to remove heat ( $Q_L$ ) from the refrigerated space.

For a refrigerator  $COP_R = \frac{\text{Desired output}}{\text{Required input}}$

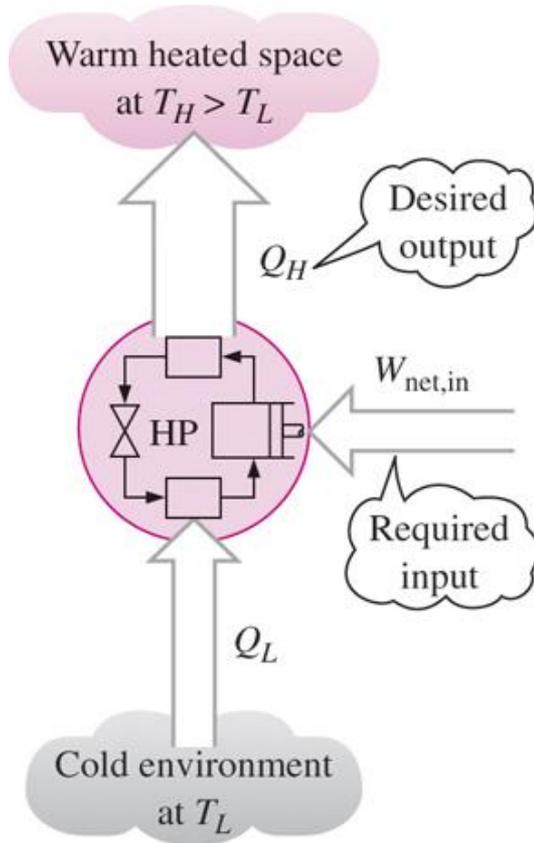
$$= \frac{Q_L}{W_{net,in}} \quad (\text{or} \quad \frac{\dot{Q}_L}{\dot{W}_{net,in}})$$

$$W_{net,in} = Q_H - Q_L \quad (\text{kJ})$$

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

Notice that  $COP_R$ , can be greater than unity.

## Heat Pumps:



➤ another device that transfer heat from  $T_L$  to  $T_H$ .

➤ objective is different : maintain a heated space at high temperature.

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

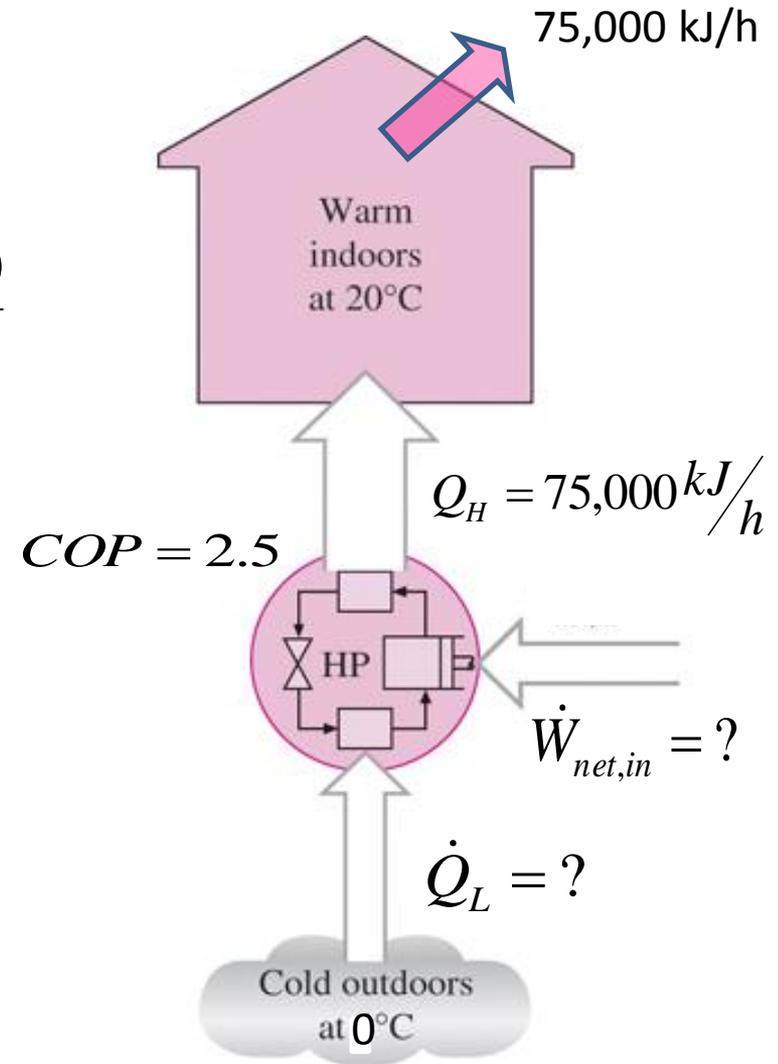
The objective of a heat pump is to supply heat  $Q_H$  into the warmer space.

**EXAMPLE:**

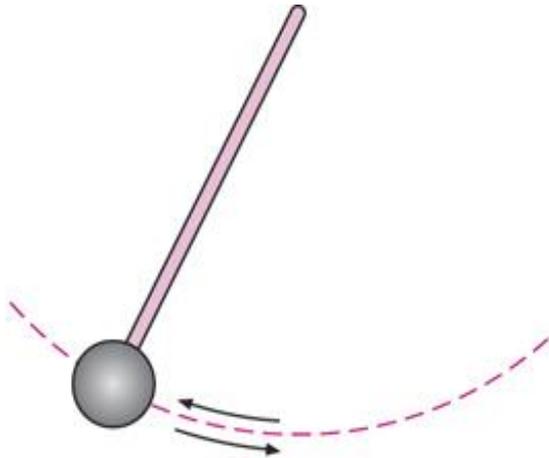
$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} \rightarrow \dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{75,000}{2.5}$$

$$\dot{W}_{net,in} = 30,000 \text{ kJ/h (or } 8.33 \text{ kW)}$$

$$\begin{aligned} \dot{Q}_L &= \dot{Q}_H - \dot{W}_{net,in} = (75,000 - 30,000) \\ &= 45,000 \text{ kJ/h} \end{aligned}$$



## REVERSIBLE AND IRREVERSIBLE PROCESSES:



(a) Frictionless pendulum

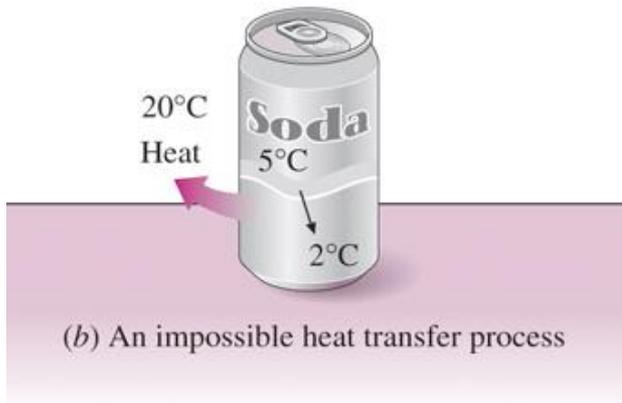
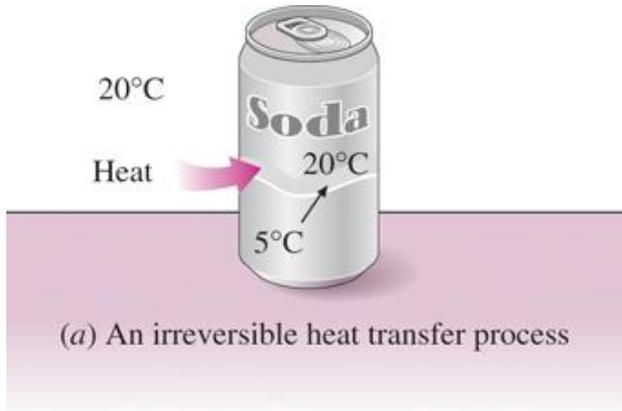
A pendulum could be a reversible process if it were frictionless



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

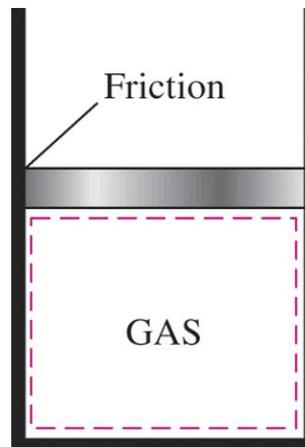
- A process is reversible if, after it has occurred, both the system and the surroundings can be returned to their original states.
- If the system can not be restored to its initial state then the process is called irreversible.
- The reversible processes do not occur in nature. They are only idealization of actual processes.
- Reversible processes are important because they provide the maximum work from work-producing devices and the minimum work input to devices that absorb work to operate. (**theoretical limitation of performance**)
- The more close we approximate a reversible process the better.

## Irreversibilities:



(a) Heat transfer through a temperature difference is irreversible, and (b) the reverse process is impossible.

- The factors that cause a process to be irreversible are called irreversibilities.
- They include friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.
- When designing something we try to lower the irreversibilities.

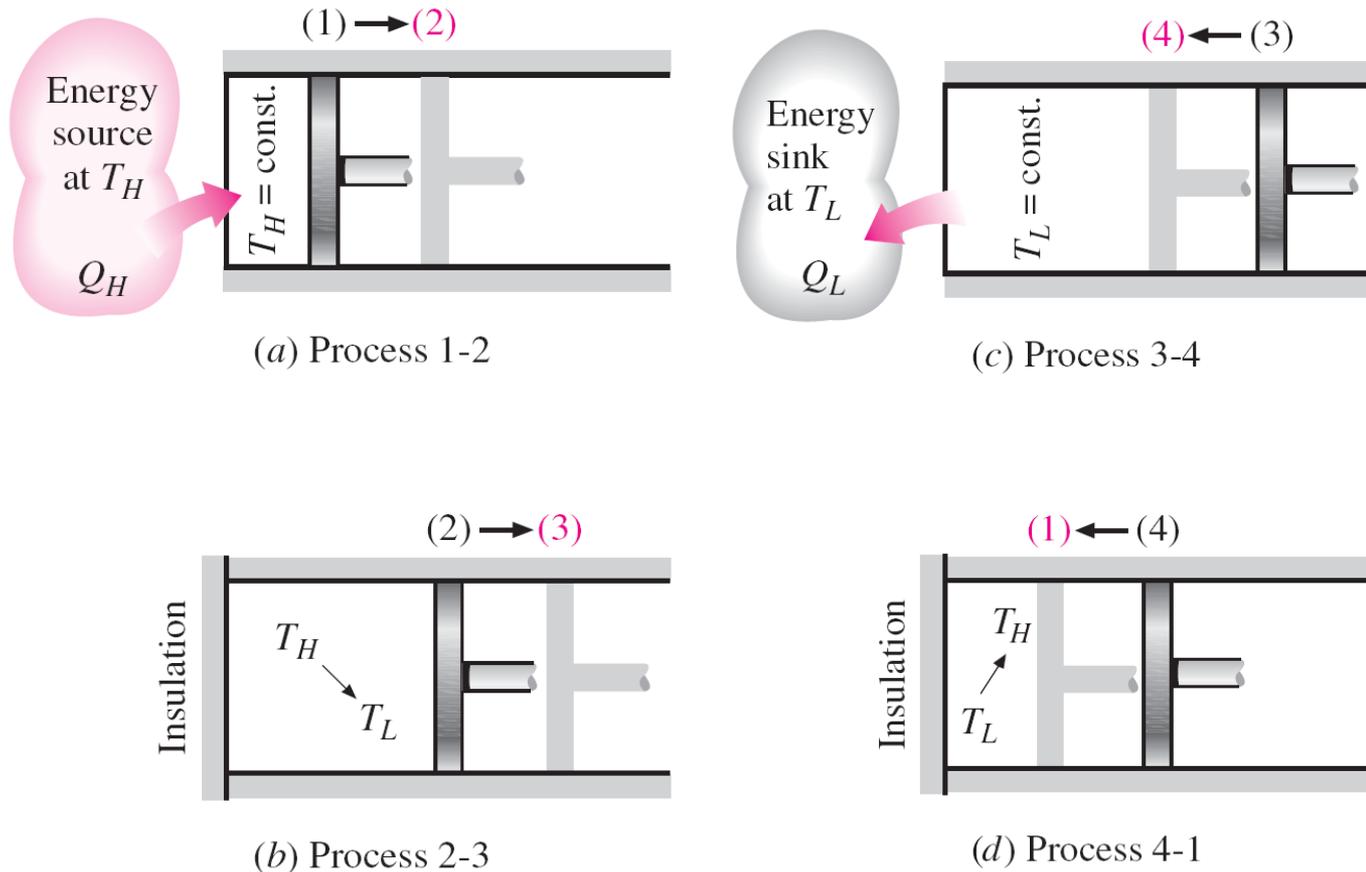


Friction renders a process irreversible.

## **THE CARNOT CYCLE:**

- **A reversible cycle, i.e. limiting case for both an engine and a refrigerator.**
- **The Carnot engine is the heat engine that converts heat into work with the highest possible efficiency.**
- **The Carnot refrigerator is the refrigerator that uses the minimum amount of work to cool a space**
- **The Carnot cycle is composed of four reversible processes (two isothermal and two adiabatic).**
- **Can be expected either in a closed system or a steady-flow system.**

## Gas in an adiabatic piston-cylinder device:



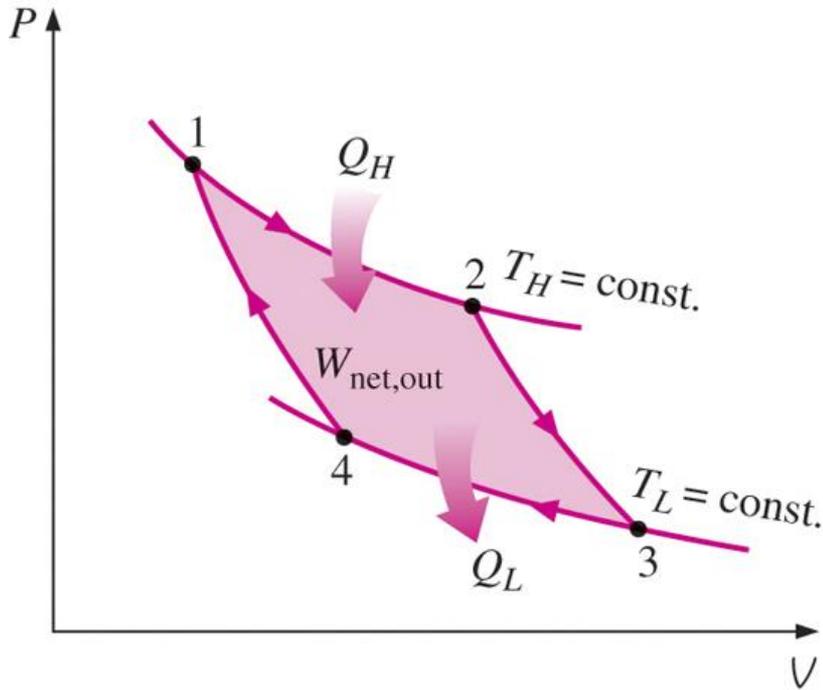
**Execution of the Carnot cycle in a closed system.**

**Reversible Isothermal Expansion (process 1-2,  $T_H = \text{constant}$ )**

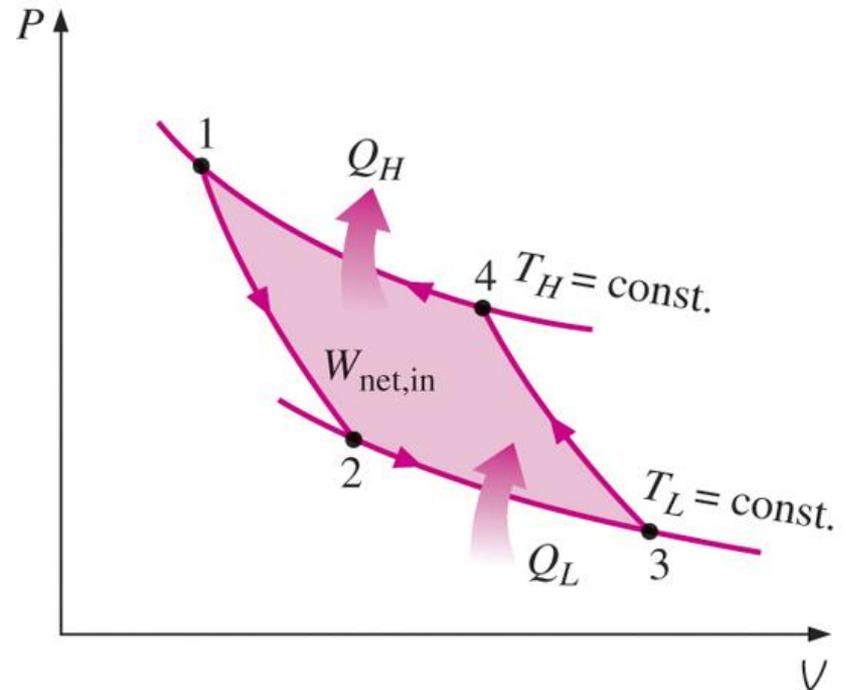
**Reversible Adiabatic Expansion (process 2-3, temperature drops from  $T_H$  to  $T_L$ )**

**Reversible Isothermal Compression (process 3-4,  $T_L = \text{constant}$ )**

**Reversible Adiabatic Compression (process 4-1, temperature rises from  $T_L$  to  $T_H$ )**



**P-V diagram of the Carnot cycle.**



**P-V diagram of the reversed Carnot cycle.**

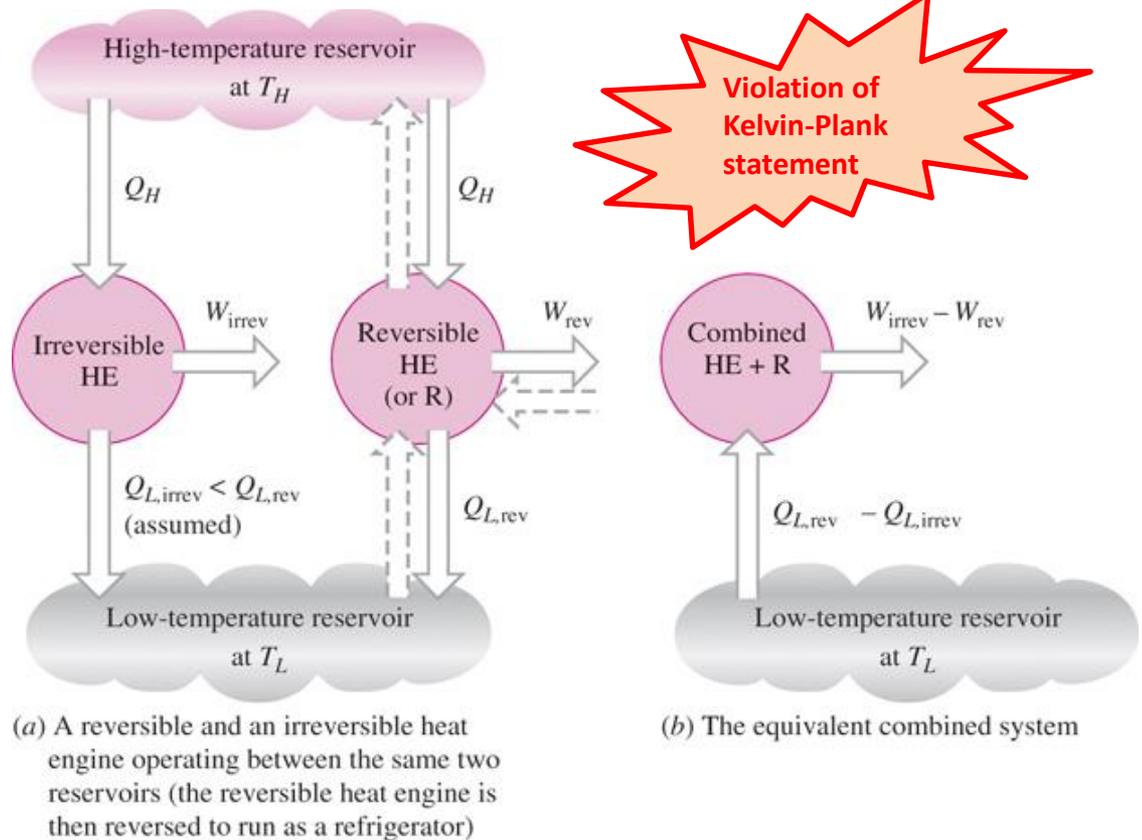
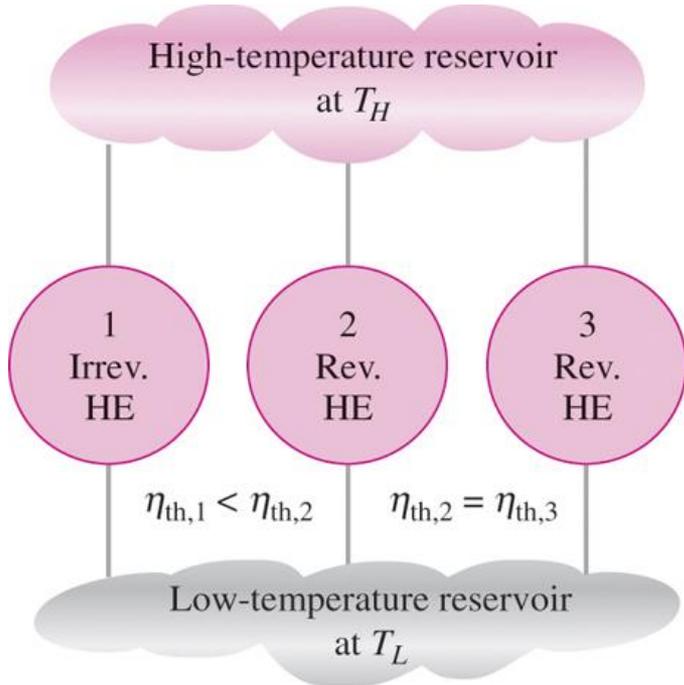
### **The Reversed Carnot Cycle:**

**The Carnot heat-engine cycle is a totally reversible cycle.**

**Therefore, all the processes that comprise it can be *reversed*, in which case it becomes the **Carnot refrigeration cycle**.**

## THE CARNOT PRINCIPLES:

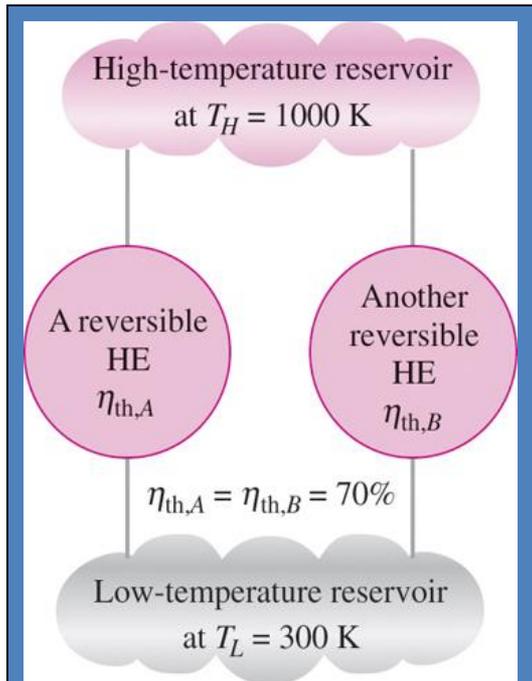
1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.
2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.



The Carnot principles.

Proof of the first Carnot principle.

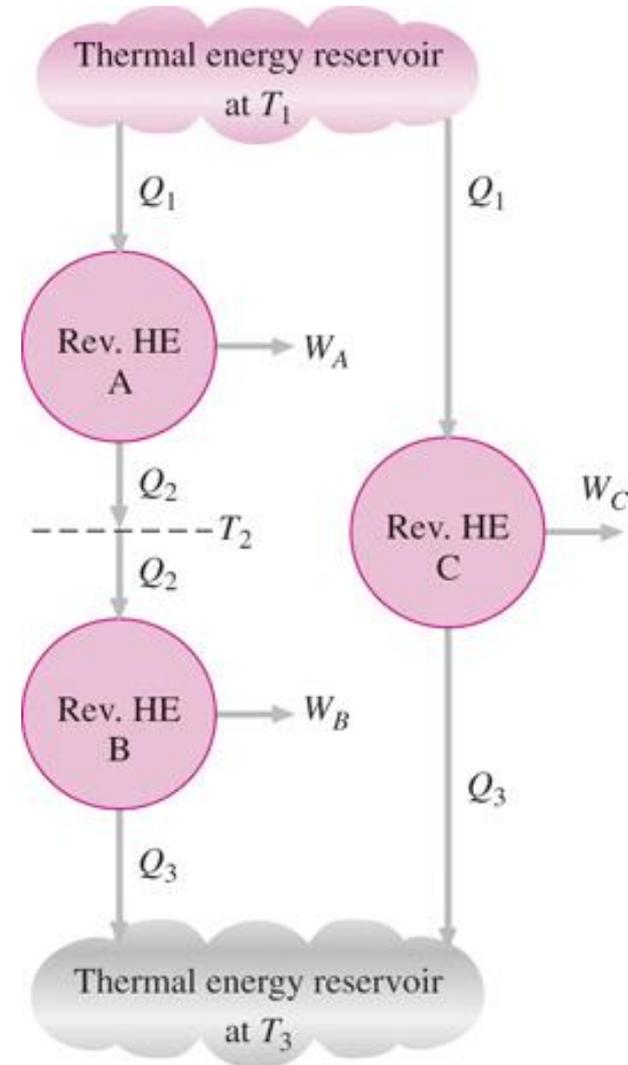
## THE THERMODYNAMIC TEMPERATURE SCALE:



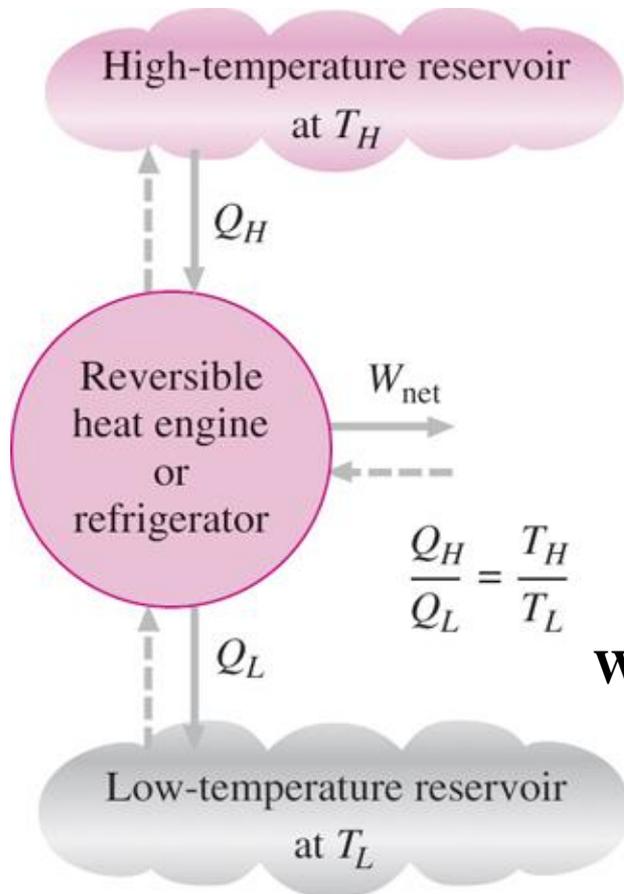
**All reversible heat engines operating between the same two reservoirs have the same efficiency.**

**A temperature scale that is independent of the properties of the substances that are used to measure temperature is called a thermodynamic temperature scale.**

**Such a temperature scale offers great conveniences in thermodynamic calculations.**



**The arrangement of heat engines used to develop the thermodynamic temperature scale.**



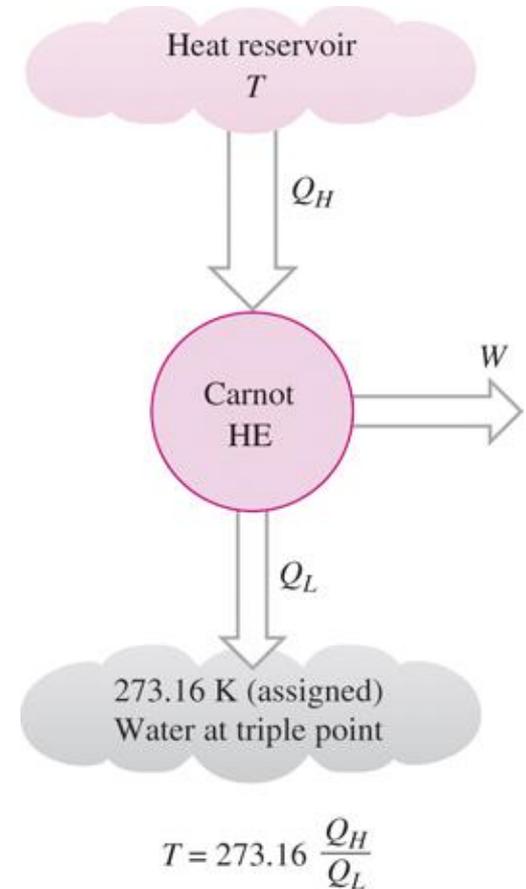
**For a reversible heat engine operating between two reservoirs:**

$$\frac{Q_H}{Q_L} = \frac{\phi(T_H)}{\phi(T_L)}$$

**With Kelvin scale**  $\longrightarrow \phi(T) = T$

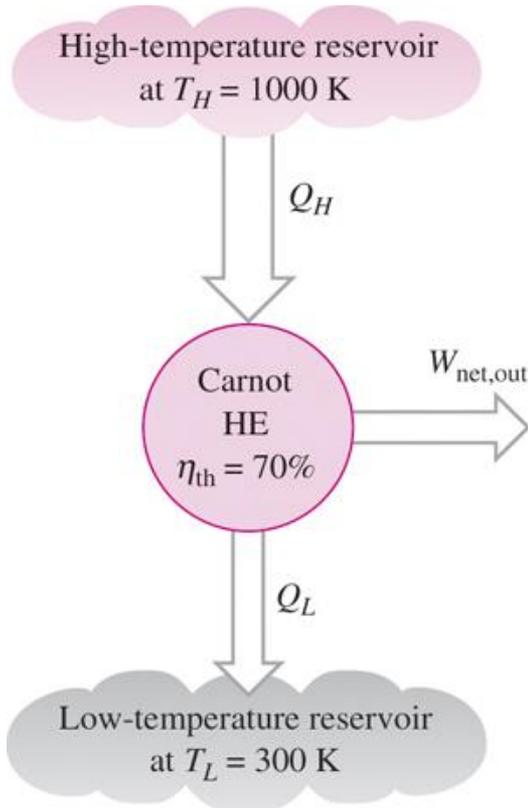
$$\left(\frac{Q_H}{Q_L}\right) = \frac{T_H}{T_L}$$

**For reversible cycles, the heat transfer ratio  $Q_H/Q_L$  can be replaced by the absolute temperature ratio  $T_H/T_L$ .**

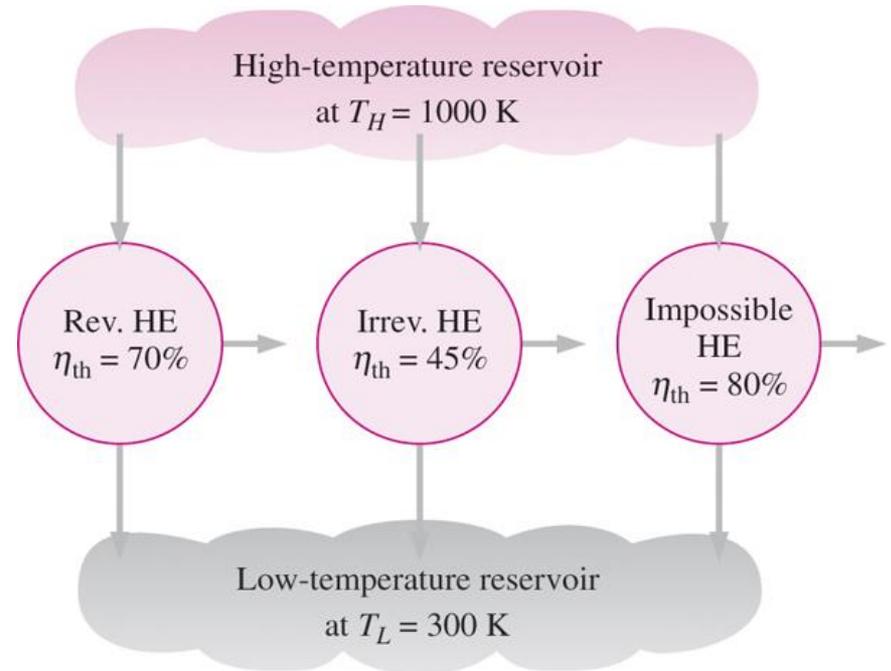


**A conceptual experimental setup to determine thermodynamic temperatures on the Kelvin scale by measuring heat transfers  $Q_H$  and  $Q_L$ .**

## THE CARNOT HEAT ENGINE:



**The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.**



**No heat engine can have a higher efficiency than a reversible heat engine operating between the same high- and low-temperature reservoirs.**

**For any heat engine:**

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

**For a carnot engine(i.e. any reversible heat engine):**

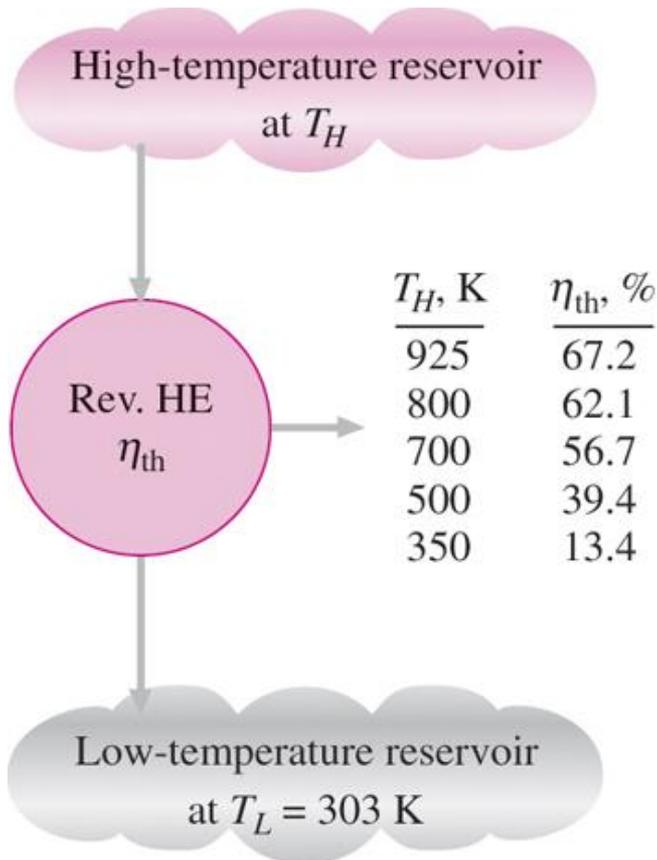
$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

**Carnot efficiency:** This is the highest efficiency a heat engine operating between the two reservoirs at  $T_L$  and  $T_H$  can have.

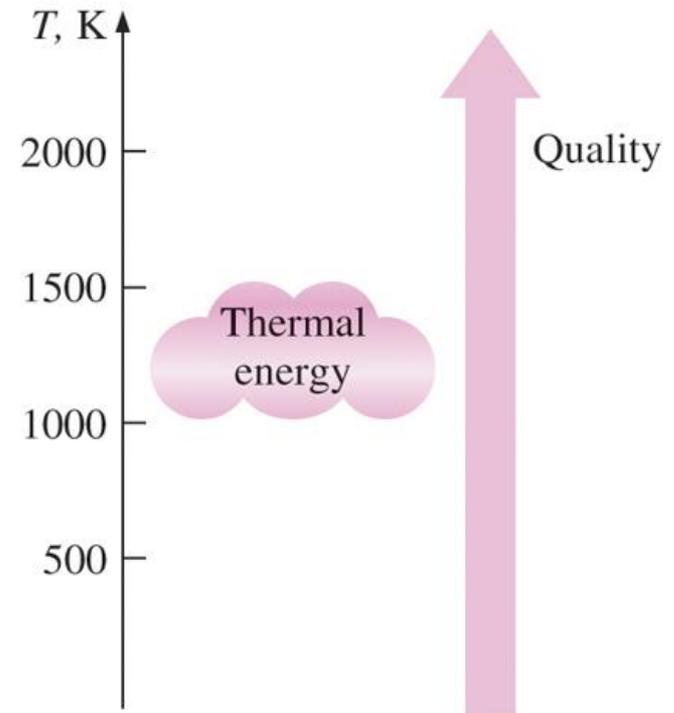
**For a steam power plant operating between  $T_H=750K$  and  $T_L=300K$  the maximum efficiency is 60%.(In practicing they are under 40%)**

## The Quality of Energy:

The carnot efficiency implies that, the higher the temperature  $T_H$ , the higher the efficiency and hence the higher the quality of energy.

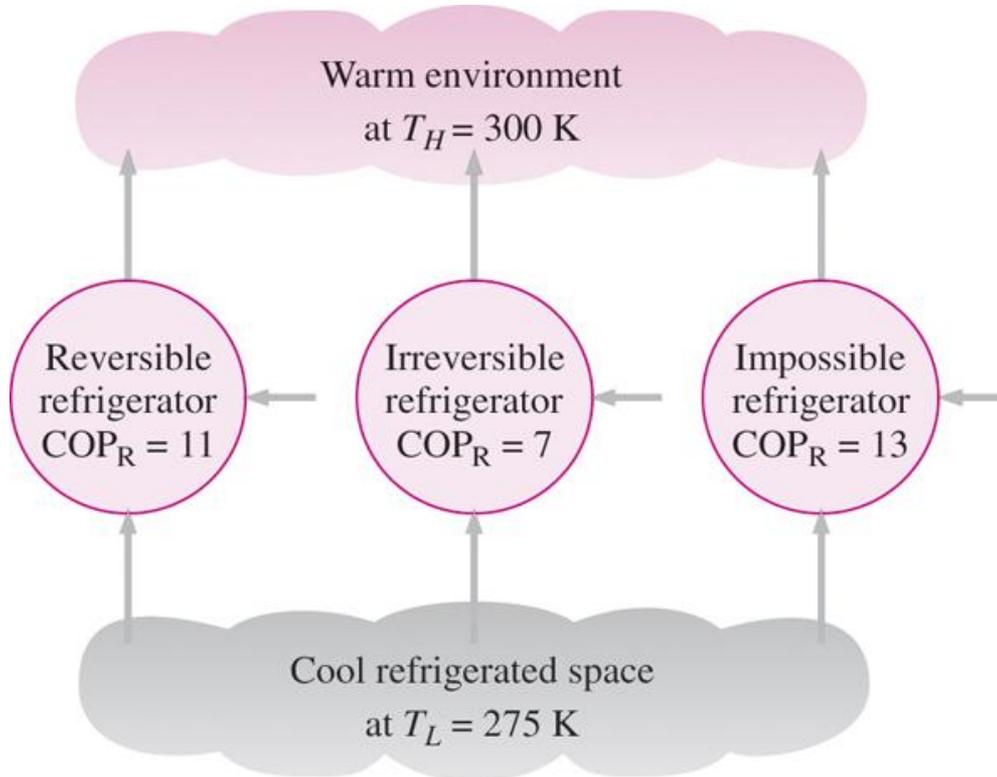


The fraction of heat that can be converted to work as a function of source temperature.



The higher the temperature of the thermal energy, the higher its quality.

## THE CARNOT REFRIGERATOR AND HEAT PUMP:



$$COP_{HP} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

**No refrigerator can have a higher COP than a reversible refrigerator operating between the same temperature limits.**

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

**For a carnot refrigerator:**

$\frac{Q_H}{Q_L}$  replace by  $\frac{T_H}{T_L}$

$$\Rightarrow COP_{R,rev} = \frac{1}{\frac{T_H}{T_L} - 1}$$



**Highest COP between the limits TL and TH**

**For a carnot heat pump:**

$\frac{Q_L}{Q_H}$  replace by  $\frac{T_L}{T_H}$

$$\Rightarrow COP_{HP,rev} = \frac{1}{1 - \frac{T_L}{T_H}}$$