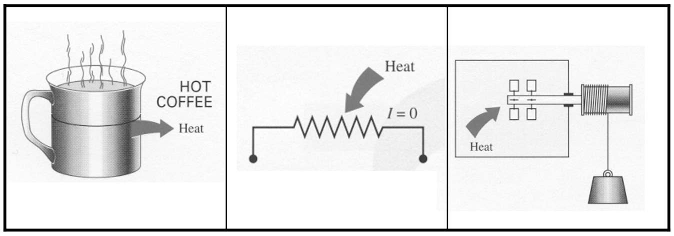
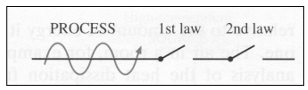
Second Law of Thermodynamics





- A process will not occur unless it satisfies ***both*** the first and the second laws of thermodynamics

Thermal Energy Reservoir

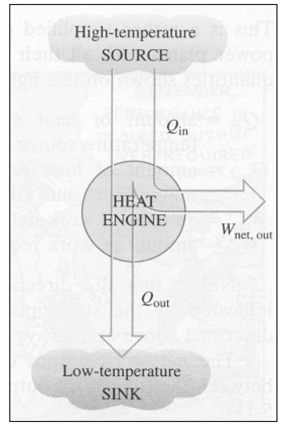
- A ***thermal energy reservoir*** is a hypothetical body that can ***supply*** or ***absorb*** finite amounts of heat without undergoing any change in temperature (large bodies of water, atmospheric air, and two-phase systems

- Any physical body whose thermal energy capacity is large relative to the amount of energy it supplies or absorbs can be modeled as a reservoir (e.g. the air in a room)

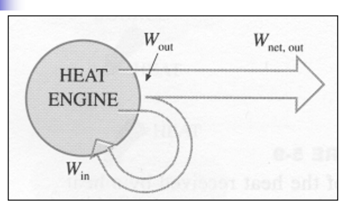
- A reservoir that supplies energy in the form of heat is called a ***source***, and one that absorbs energy in the form of heat is called a ***sink***

Heat Engines

1. They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, *etc.*)
2. They convert part of this heat to work (usually in the form of a rotating shaft)
3. They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.)
4. They operate on a cycle

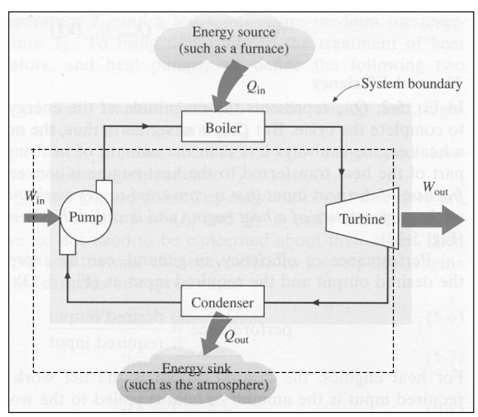


Steam Power Plant



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

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

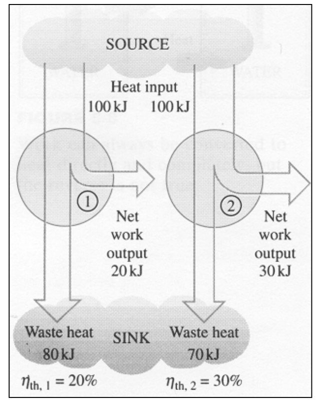


Thermal Efficiency

- The fraction of the heat input that is converted to net work output is called the ***thermal efficiency***

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

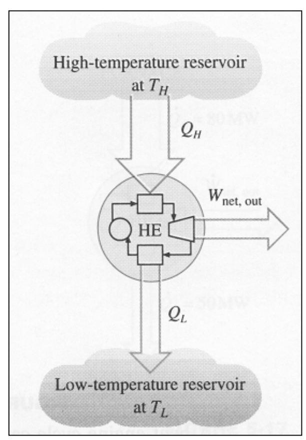


Thermal Efficiency

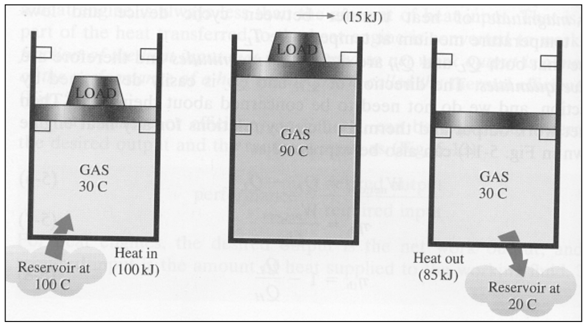
$$W_{net,out} = Q_H - Q_L$$

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

- **Q_H**: Magnitude of heat transfer between cyclic device and high-temperature medium at temperature T_H
- **Q_L**: Magnitude of heat transfer between cyclic device and low-temperature medium at temperature T_L



Can We Save Q_{out}?

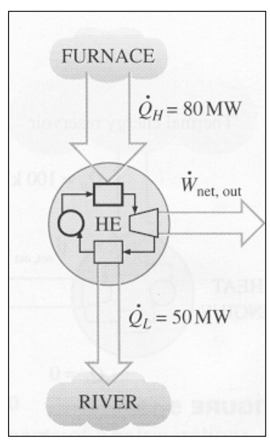


- Every heat engine must waste some energy by transferring it to a low-temperature reservoir in order to complete the cycle.

Example

Determine:

1. Net power output,
2. The thermal efficiency for this heat engine



Kelvin-Plank Statement

- ***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.***

- ***No*** heat engine can have a thermal efficiency of 100 percent.

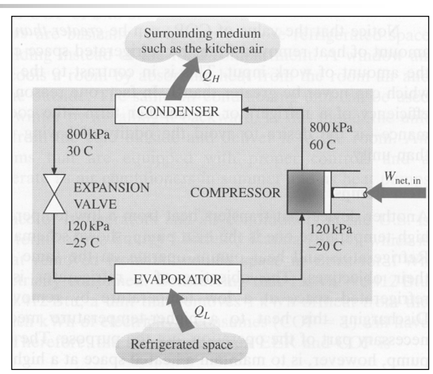
- This limitation applies to both the idealized and the actual heat engines.

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

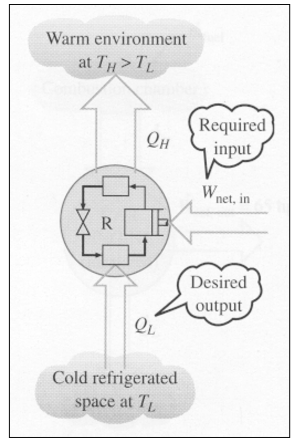


Coefficient Of Performance (COP)

$$COP_R = \frac{\text{desired output}}{\text{required input}} = \frac{Q_L}{W_{net,in}}$$

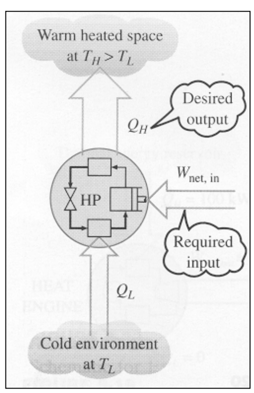
$$W_{net,in} = Q_H - Q_L$$

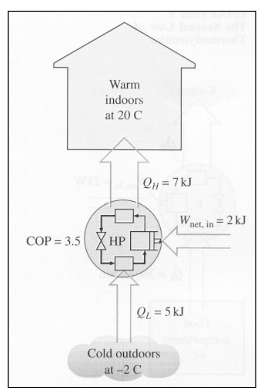
$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H / Q_L - 1}$$



- COP_R can be greater than ***unity!***

Heat Pumps





- The objective of a heat pump, is to maintain a heated space at a high temperature

Coefficient of Performance

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

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

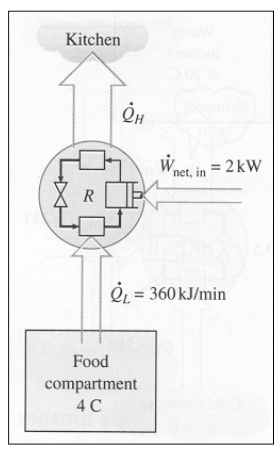
$$\boxed{COP_{HP} = COP_R + 1}$$

- Coefficient of performance of a heat pump is ***always*** greater than unity.
- A heat pump will function, at worst, as a resistance heater, supplying as much energy to the house as it consumes

Example

Determine:

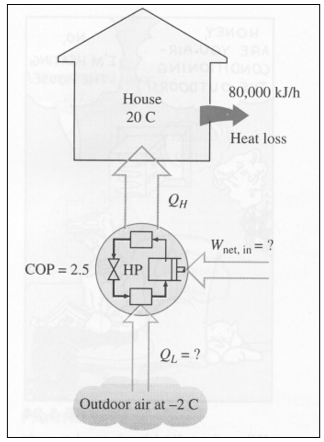
1. COP of the refrigerator,
2. Rate of heat discharge to the room.



Example

Determine:

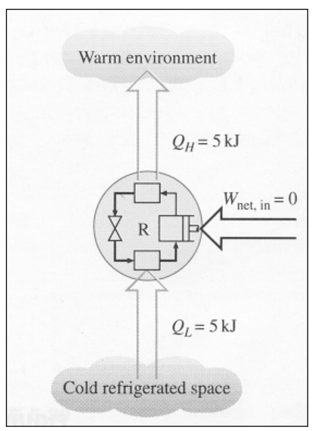
1. The power consumed by the heat pump and
2. The rate at which heat is extracted from the cold outdoor air



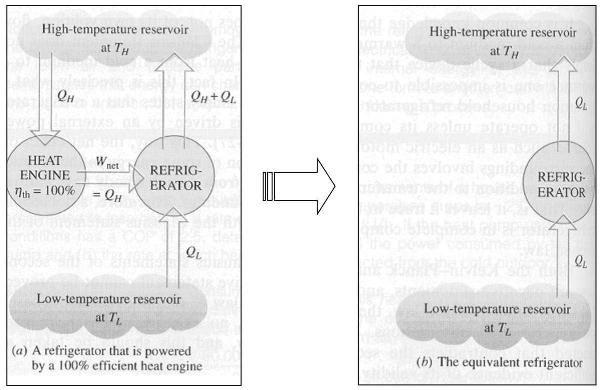
Clausius Statement

- ***It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower temperature body to a higher-temperature body***

- Clausius and the Kelvin-Planck statements are two equivalent expressions of the second law of thermodynamics



Equivalence of the Two Statements

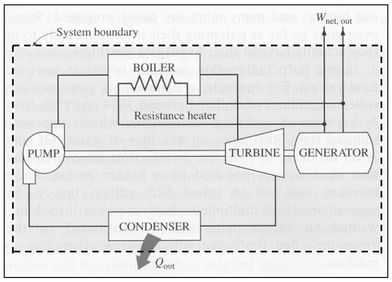


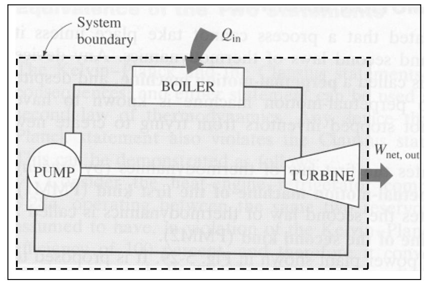
- A violation of the Kelvin-Planck statement results in the violation of the Clausius statement.

Perpetual-Motion Machines (PMM)

- A device that violates the first law of thermodynamics is called a perpetual-motion machine of the first kind (***PMM1***)
- A device that violates the second law of thermodynamics is called a perpetual-motion machine of the second kind (***PMM2***).

Perpetual-Motion Machines



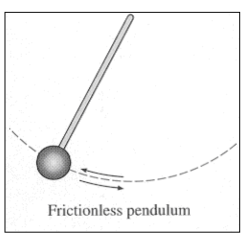


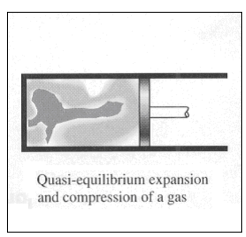
This system is creating energy at a rate of $\dot{Q}_{out} + \dot{W}_{net,out}$ which is a violation of the first law (PMM1).

This system satisfies the first law but violates the second law, and therefore it will not work (PMM2).

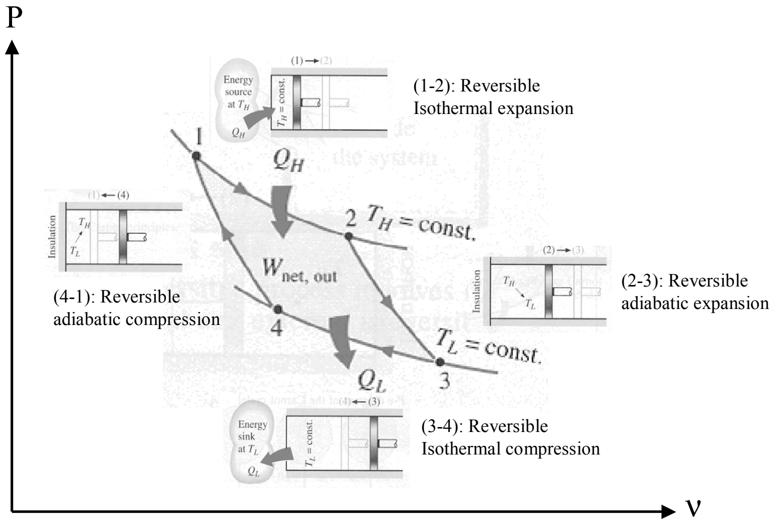
Reversible & Irreversible Processes

- A ***reversible process*** is defined as a process that can be reversed without leaving any trace on the surroundings. Processes that are not reversible are called ***irreversible*** processes.


Frictionless pendulum


Quasi-equilibrium expansion and compression of a gas

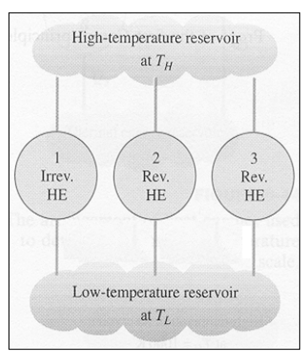
The *Carnot* Cycle (1824)



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.



$\eta_{th,1} < \mu_{th,2}$ $\eta_{th,2} = \mu_{th,3}$

The Carnot Heat Engine

$$\eta_{th} = 1 - \frac{Q_L}{Q_H} \qquad \left[\frac{Q_H}{Q_L}\right]_{rev} = \frac{T_H}{T_L}$$

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

T_L & T_H are absolute temperatures

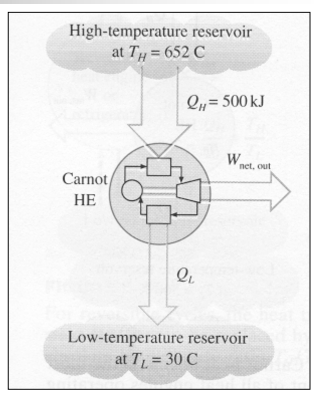
- ***Carnot Efficiency*** is *the* ***highest*** efficiency a heat engine operating between the two thermal energy reservoirs at temperatures T_L and T_H can have.

Example

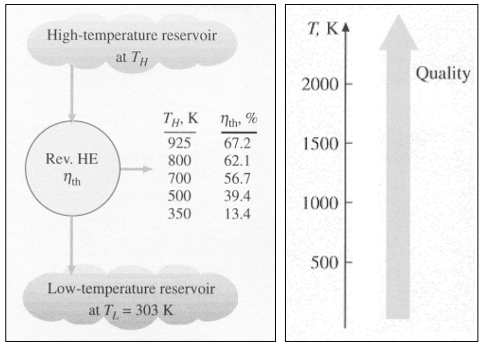
Determine:

(a) Thermal efficiency,

(b) Amount of heat rejected to the sink



Energy has Quality!



- The higher the temperature, the higher the quality of the energy.

Carnot Refrigerator & Heat Pump

$$COP_R = \frac{1}{Q_H / Q_L - 1} \quad \text{and} \quad COP_{HP} = \frac{1}{1 - Q_L / Q_H}$$

$$\boxed{COP_{R,rev} = \frac{1}{T_H / T_L - 1}} \quad \boxed{COP_{HP,rev} = \frac{1}{1 - T_L / T_H}}$$

- All actual refrigerators or heat pumps operating between these temperature limits (T_L and T_H) will have lower coefficients of performance.

Example

- Determine the minimum power required to drive this heat pump unit