Refrigerators, heat pumps, and the Carnot cycle

Second Law of Thermodynamics

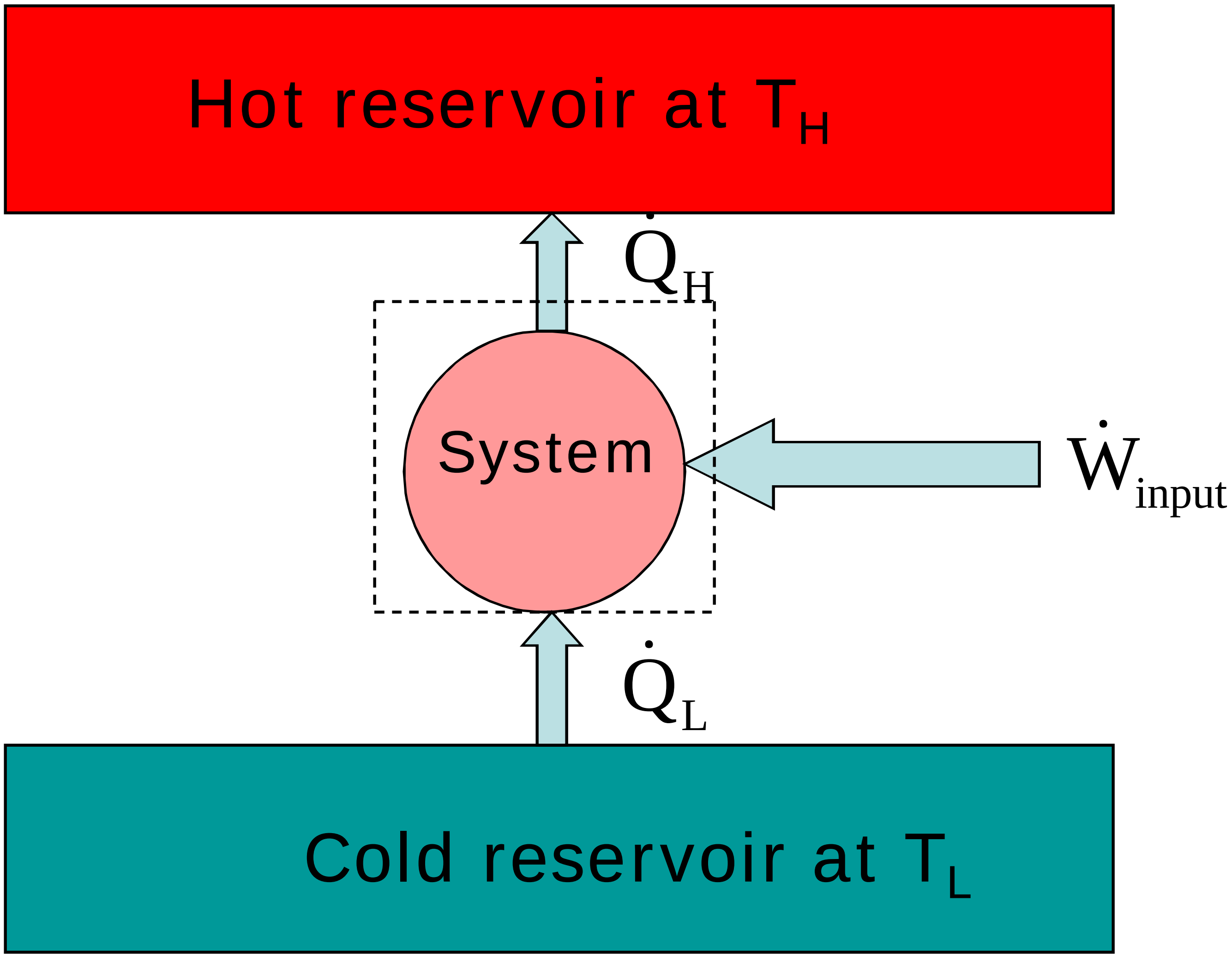
Review--Heat Engine or Cycle Efficiency

$$\eta = \frac{Net\,Work\ Output}{Heat\ Energy\ Input}$$

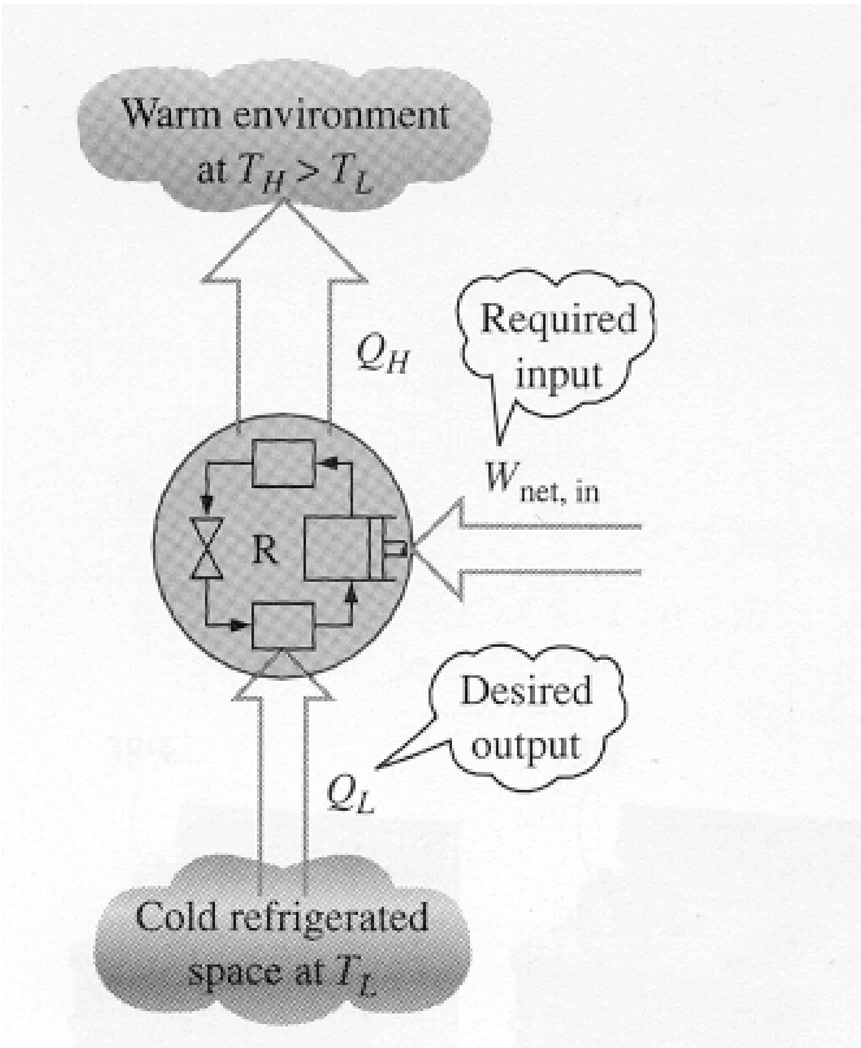
$$\eta = \frac{\dot{W}_{output}}{\dot{Q}_H} = \frac{W_{output}}{Q_H} = \frac{Q_H - Q_L}{Q_H}$$

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

Refrigerators, air conditioners and heat pumps

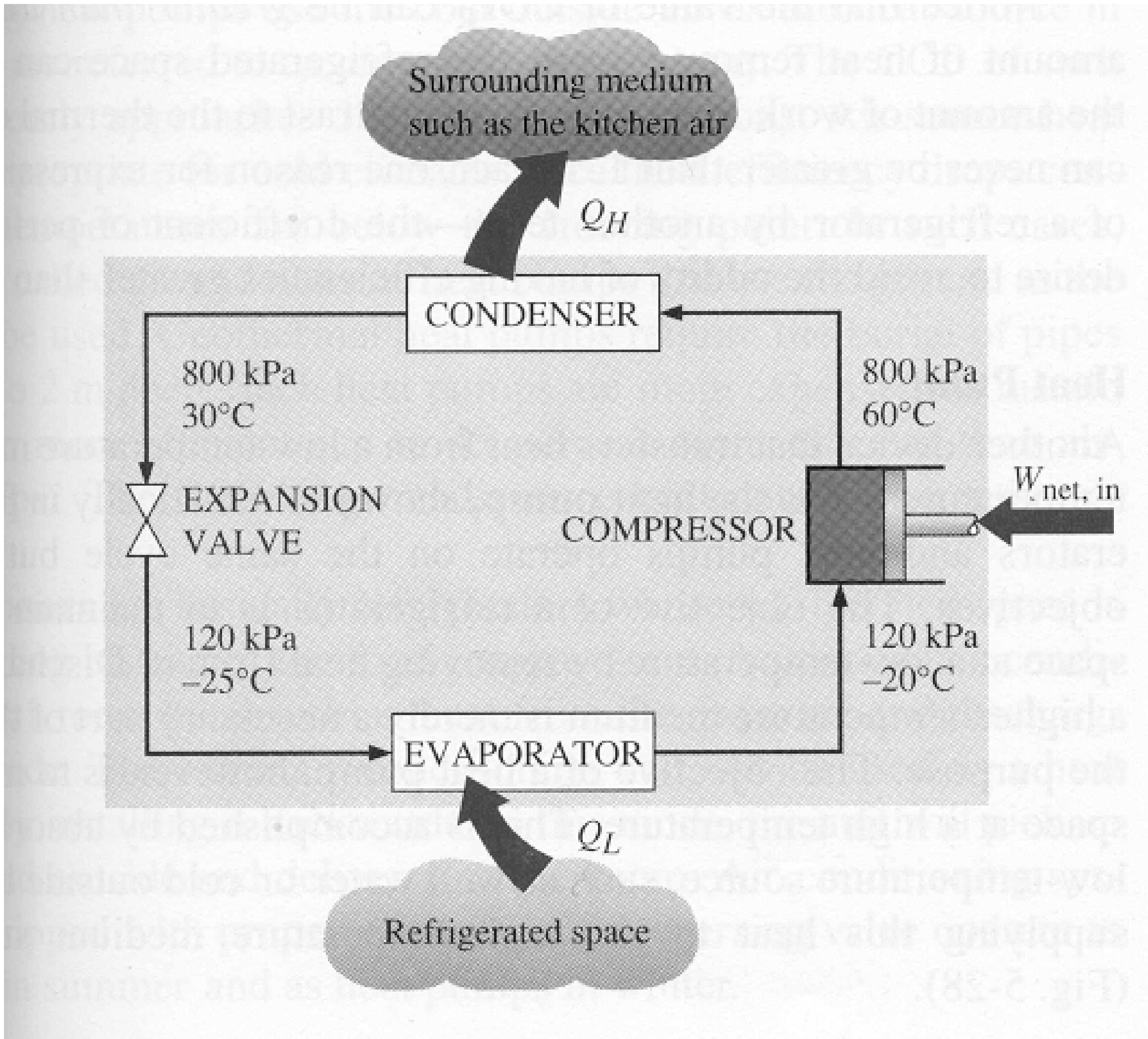


Refrigerators/‘air conditioners’



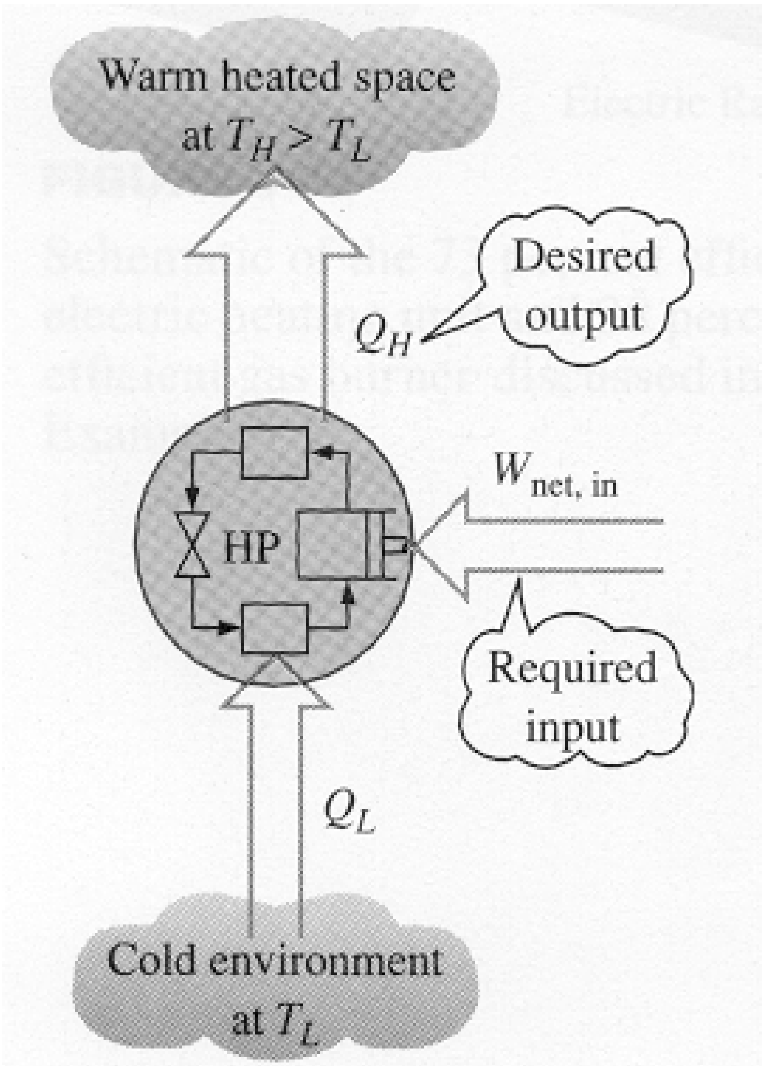
Remember: the purpose of a refrigerator or ‘air conditioner’ is to **remove** heat Q_L from a cold region at T_L.

Refrigerator



Basic components and typical operating conditions

Heat Pump



Remember: the purpose of a heat pump is to **add** heat Q_H to a warm region at T_H.

Coefficient of Performance

Refrigerators/Air conditioners

$$COP_{R/AC} = \frac{\text{Cooling Effect}}{\text{Work Input}}$$

$$COP_{R/AC} = \frac{Q_L}{W_{input}} = \frac{\dot{Q}_L}{\dot{W}_{input}}$$

Coefficient of Performance

Refrigerators/Air conditioners

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

$$COP_{R/AC} = \frac{Q_L}{Q_H - Q_L}$$

Coefficient of Performance for Heat Pumps

$$COP_{hp} = \frac{Heating\ Effect}{Work\ Input}$$

$$\mathrm{COP_{hp}} = \frac{\mathrm{Q_H}}{\mathrm{W_{input}}} = \frac{\dot{\mathrm{Q}}_\mathrm{H}}{\dot{\mathrm{W}}_\mathrm{input}}$$

Coefficient of Performance for Heat Pumps

$$COP_{hp} = \frac{Q_H}{Q_H - Q_L}$$

Perpetual Motion Machines (PMM)

- PMM1--A perpetual motion machine of the first kind violates the first law or the law of conservation of energy. An example would be an adiabatic system that supplies work with no change in internal energy, kinetic energy or potential energy.

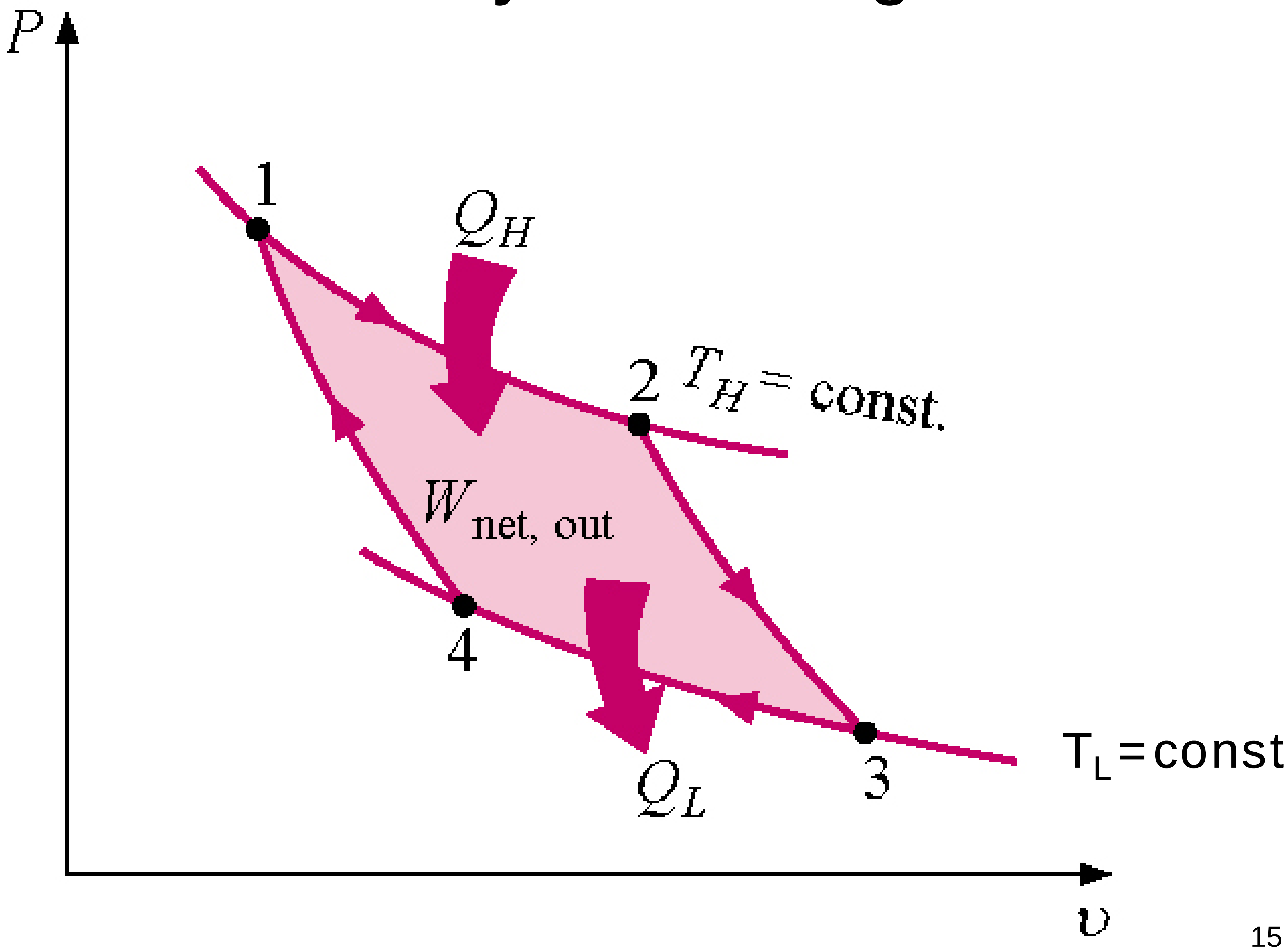
Perpetual Motion Machines (PMM)--Teamplay

- PMM2--A perpetual motion machine of the second kind violates the second law of thermodynamics.
- Your book has Figure 6-34 and goes into a correct explanation of why it violates the first law.
- The contraption in Figure 6-34 also violates the second law, as does the machine in Figure 6-35. Why?

Carnot Cycle

- Composed of four internally reversible processes.
  - Two isothermal processes
  - Two adiabatic processes

Carnot cycle for a gas.



The Carnot cycle for a gas might occur as visualized below.

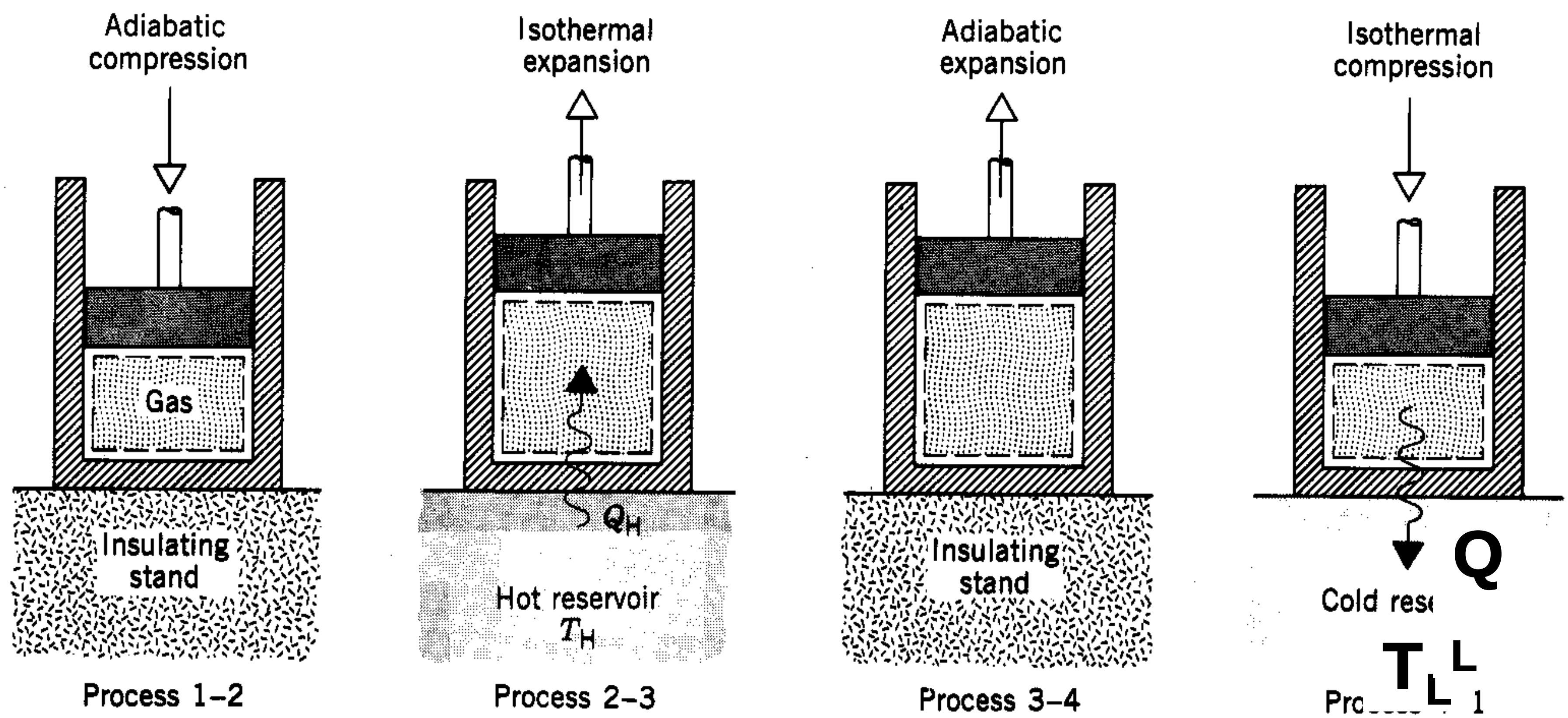
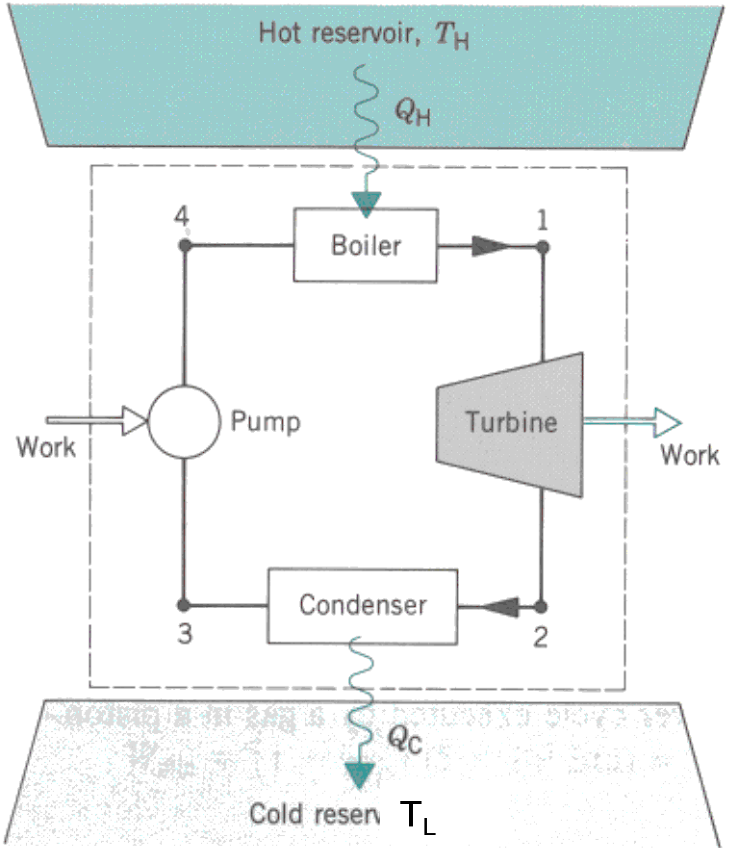
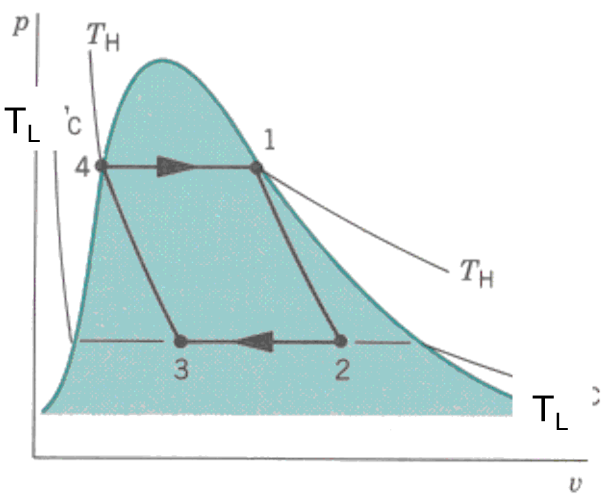


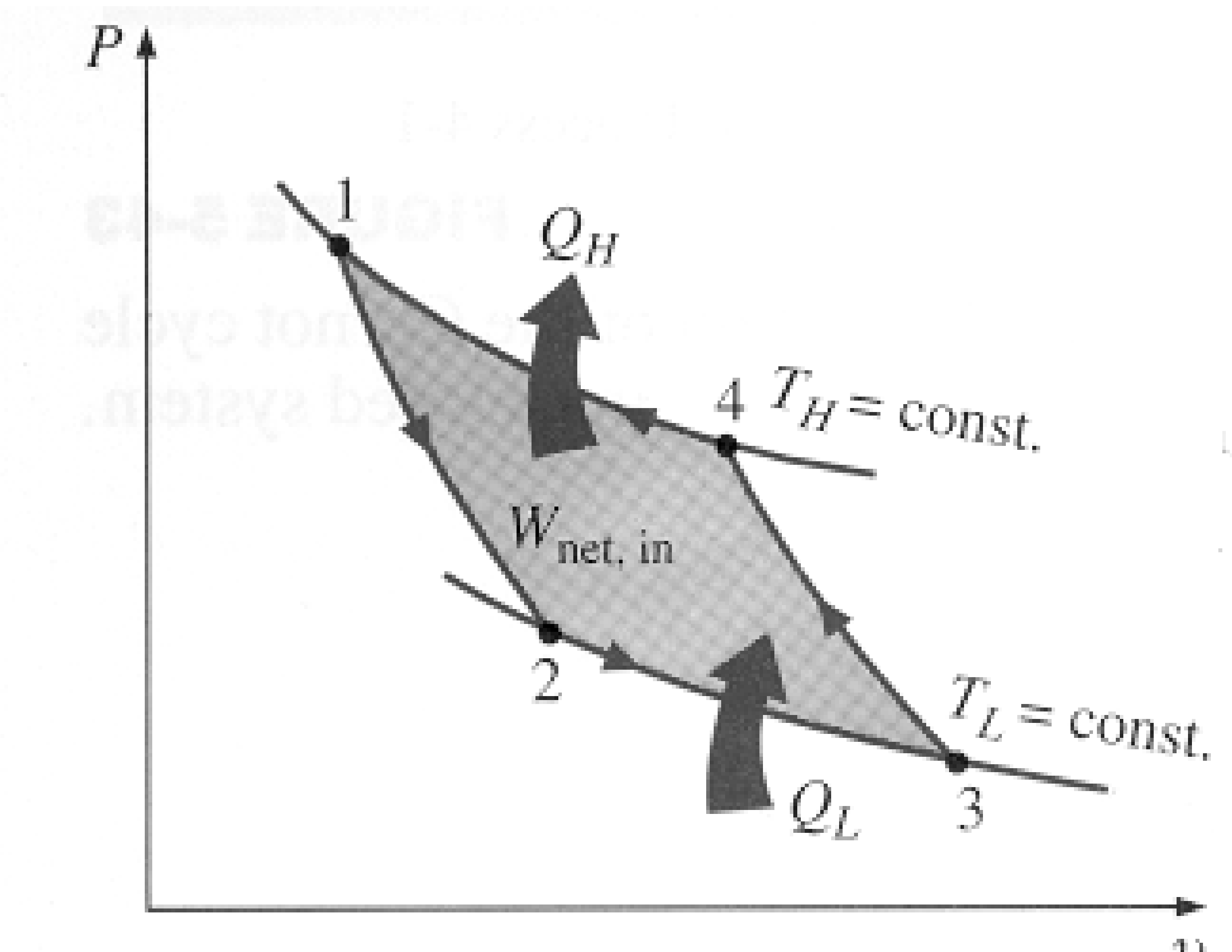
Figure 5.10 Carnot power cycle executed by a gas in a piston–cylinder assembly.





- This is a Carnot cycle involving two phases--it is still two adiabatic processes and two isothermal processes.
- It is always reversible--a Carnot cycle is reversible by definition.

Carnot refrigeration cycle for a gas.



Analytical form of KP Statement:

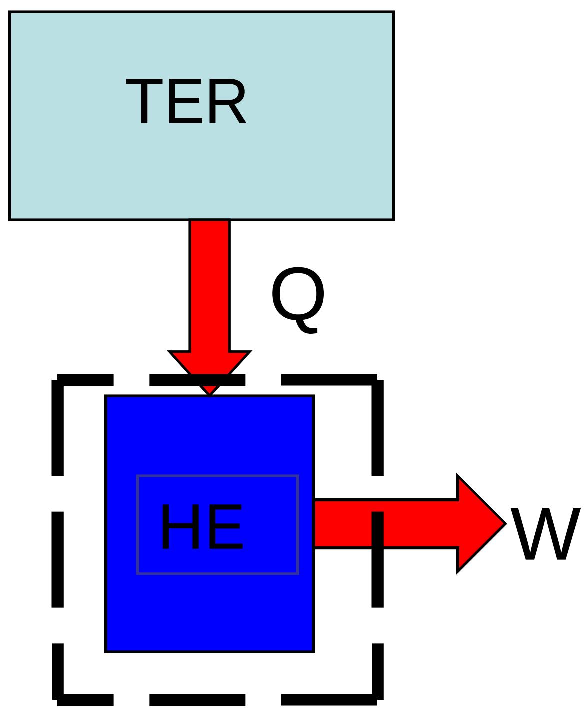
- Conservation of Energy for a cycle says
- $\Delta E = 0 = Q_{cycle} - W_{cycle}$, or

  $$Q_{cycle} = W_{cycle}$$

- We have not limited the number of heat reservoirs (or work interactions, for that matter). Q_{cycle} could be $Q_H - Q_C$, for example.

Analytical form of KP statement.

- Let us limit ourselves to the special case of one TER (thermal energy reservoir):



TEAMPLAY

- Can the system on the previous slide do work while operating in a cycle? If not, what does it violate?

Analytical form of the KP statement.

- However, it would not violate the KP statement if work were done **on** the system during the cycle, or if work were zero.

$$W_{cycle} \le 0 \qquad (\text{single reservoir})$$

Also, $Q_{cycle} \le 0 \quad (\text{single reservoir})$

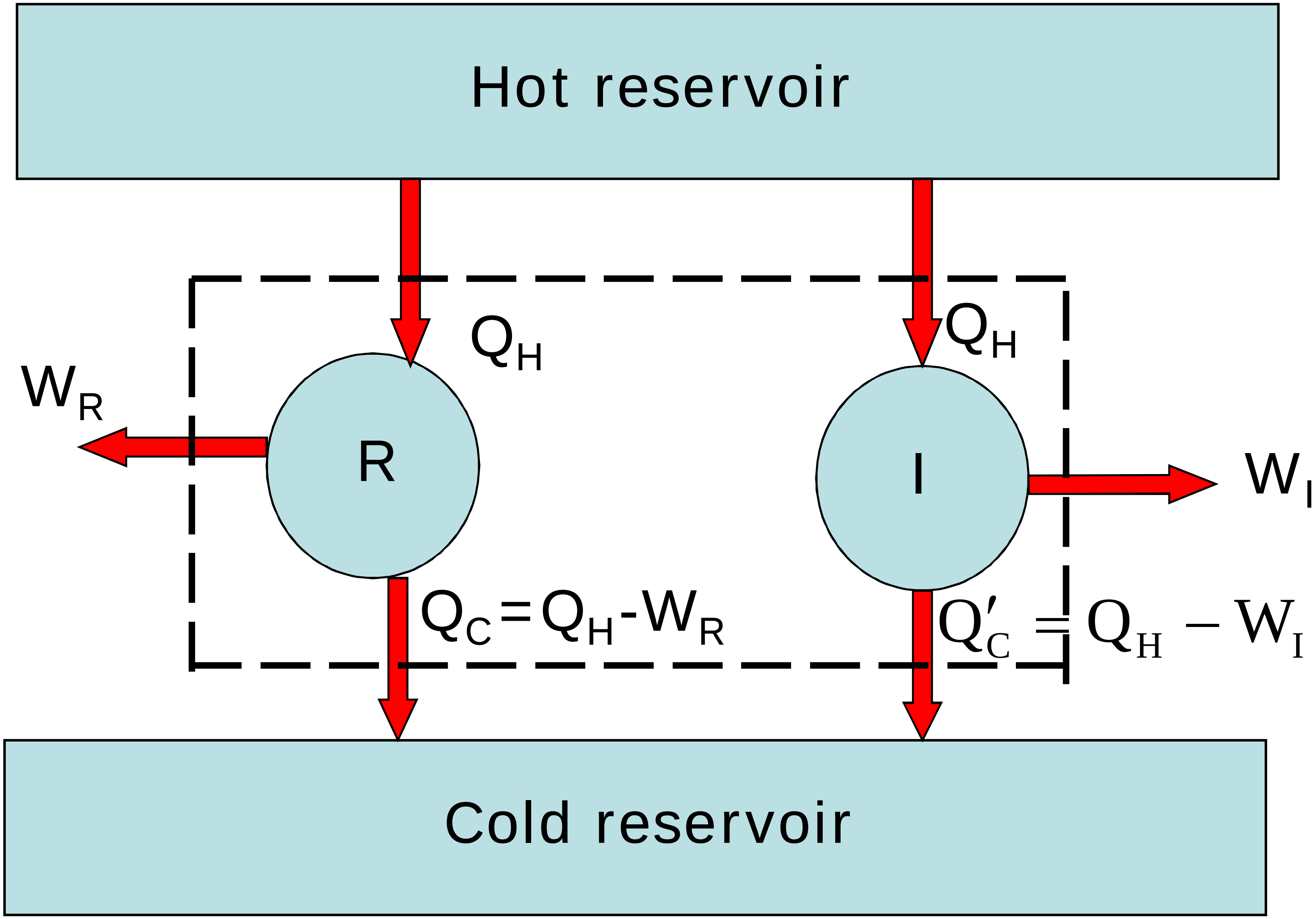
These are analytical forms of the KP statement.

Analytical forms of the KP statement.

- Both the equations may be regarded as analytical forms of the KP statement.
- It can be shown that the equality applies to reversible processes and that the inequality applies to irreversible processes.
- Consider a cycle for which the equality applies, that is $Q_{cycle} = W_{cycle}$.

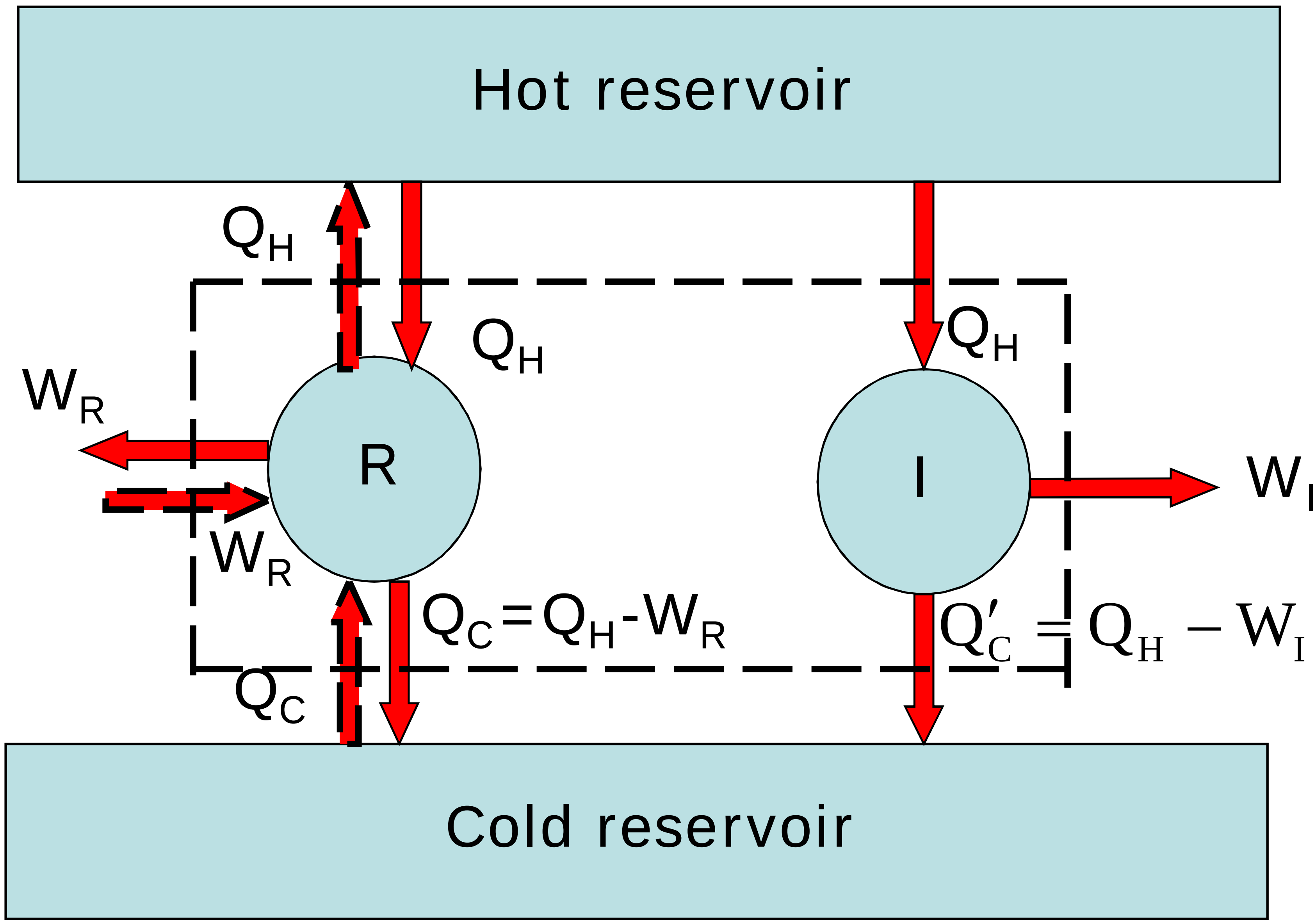
Carnot's first corollary

- The thermal efficiency of an irreversible power cycle is always less than the thermal efficiency of a reversible power cycle when each operates between the same two reservoirs.


Hot reservoir
Q_H
Q_H
W_R
R
I
W_I
$Q_C = Q_H - W_R$
$Q'_C = Q_H - W_I$
Cold reservoir

Carnot's first corollary

- Each engine receives identical amounts of heat Q_H and produces W_R or W_I.
- Each discharges an amount of heat Q to the cold reservoir equal to the difference between the heat it receives and the work it produces.


Hot reservoir
Q_H
Q_H
Q_H
W_R
R
I
W_I
W_R
$Q_C = Q_H - W_R$
$Q'_C = Q_H - W_I$
Q_C
Cold reservoir

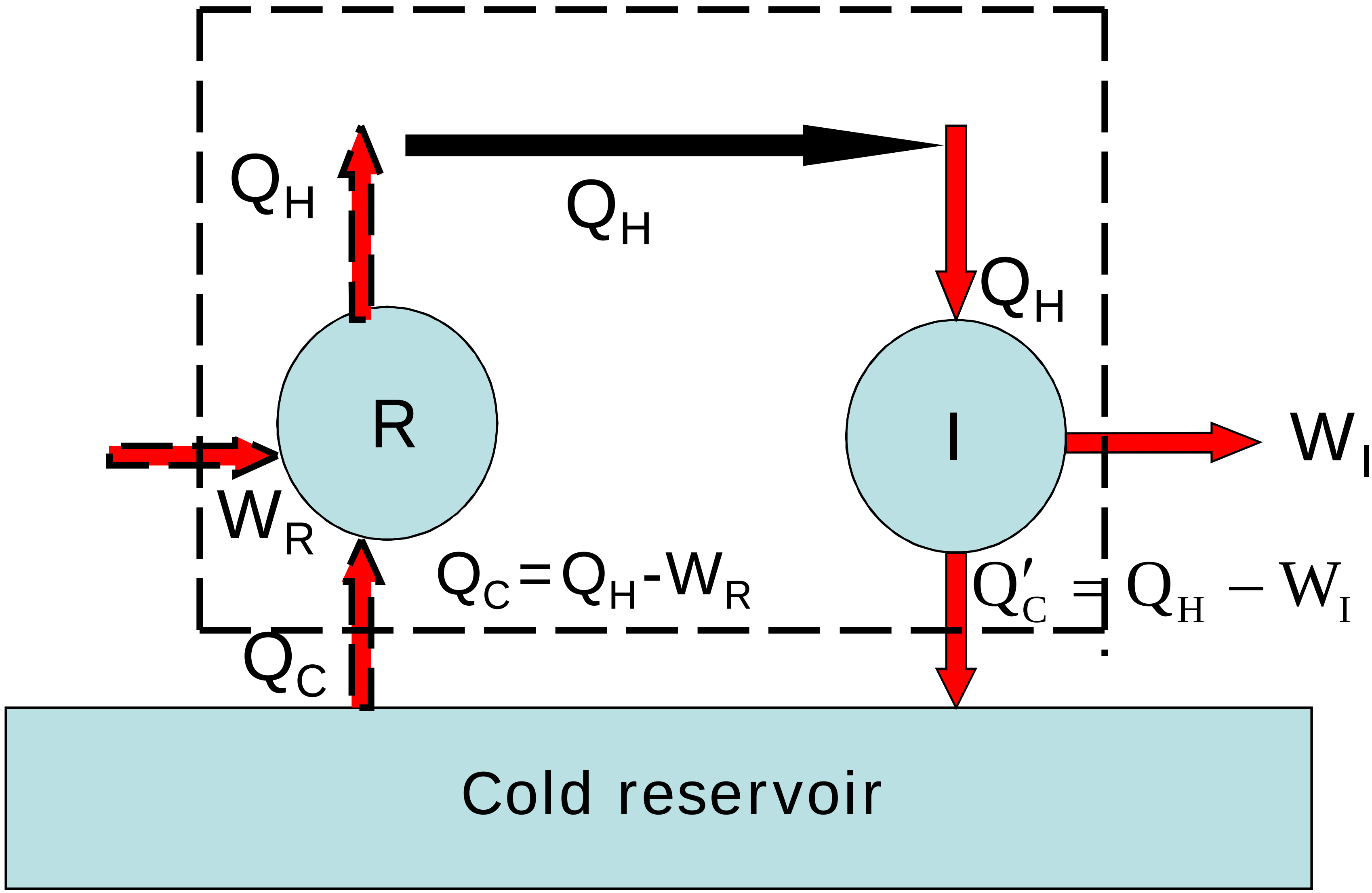
Carnot's first corollary.

- Taken together,

$$W_R + W_I = Q_H - Q_C + Q_H - Q'_C$$

- Now reverse the reversible engine.

$$-W_R + W_I = -Q_H + Q_C + Q_H - Q'_C$$


Q_H
Q_H
Q_H
R
I
W_I
W_R
Q_C=Q_H-W_R
Q'_C = Q_H − W_I
Q_C
Cold reservoir

Carnot's first corollary

$$-W_R + W_I = +Q_C - Q_C'$$

- If $W_I > W_R$, the system puts out net work and exchanges heat with one reservoir. This violates KP. So, W_I cannot be $> W_R$.

Carnot's first corollary

$$-W_R + W_I = +Q_C - Q'_C$$

- If $W_I = W_R$, $Q_C = Q'_C$

  And the irreversible engine is identical to the reversible engine, i.e., it is just the reversible engine.

Carnot's first corollary

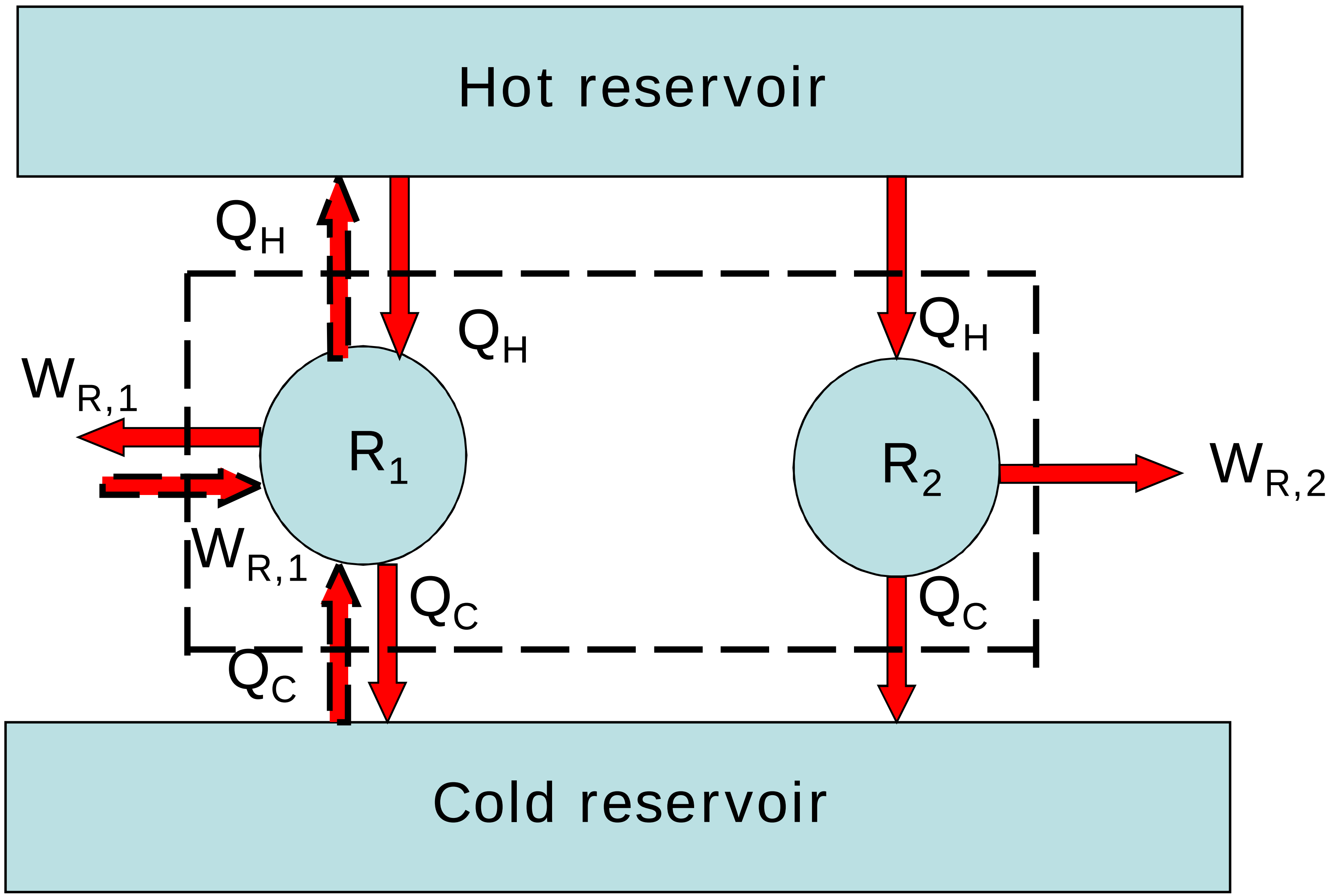
- So, $W_I < W_R$, and

$$\eta_{th,I} \equiv \frac{W_I}{Q_H} \qquad \eta_{th,R} \equiv \frac{W_R}{Q_H}$$

- So $\boxed{\eta_{th,I} < \eta_{th,R}}$

Carnot's second corollary

- All reversible power cycles operating between the same two thermal reservoirs have the same thermal efficiencies.


Hot reservoir
Q_H
Q_H
Q_H
$W_{R,1}$
R_1
R_2
$W_{R,2}$
$W_{R,1}$
Q_C
Q_C
Q_C
Cold reservoir

Carnot's second corollary

- Both engines receive Q_H, and $Q_{cycle} = 0$ and $W_{cycle} = 0$ for both engines with one reversed because they are both reversible.
- Now, with engine 1 reversed.

$$W_{cycle} = 0 = W_{R,1} - W_{R,2}$$

$$\text{and } W_{R,1} = W_{R,2}$$

Carnot's second corollary

- And

$$\eta_{th,R2} = \frac{W_{R,2}}{Q_H} = \frac{W_{R,1}}{Q_H} = \eta_{th,R1}$$

- so

$$\boxed{\eta_{th,R2} = \eta_{th,R1}}$$