RME1102
Fundamentals of Mechanical Engineering

Lecture 4

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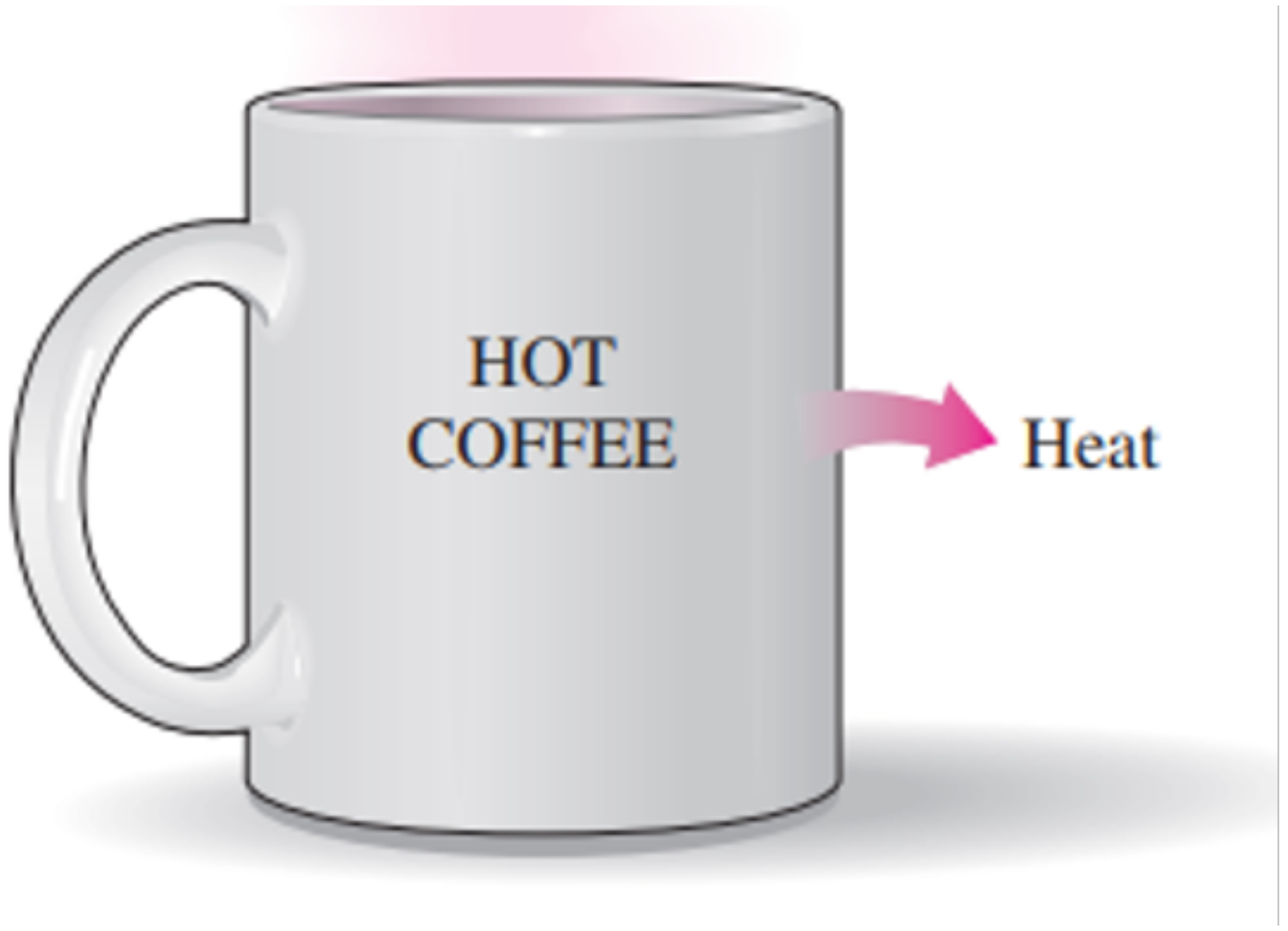
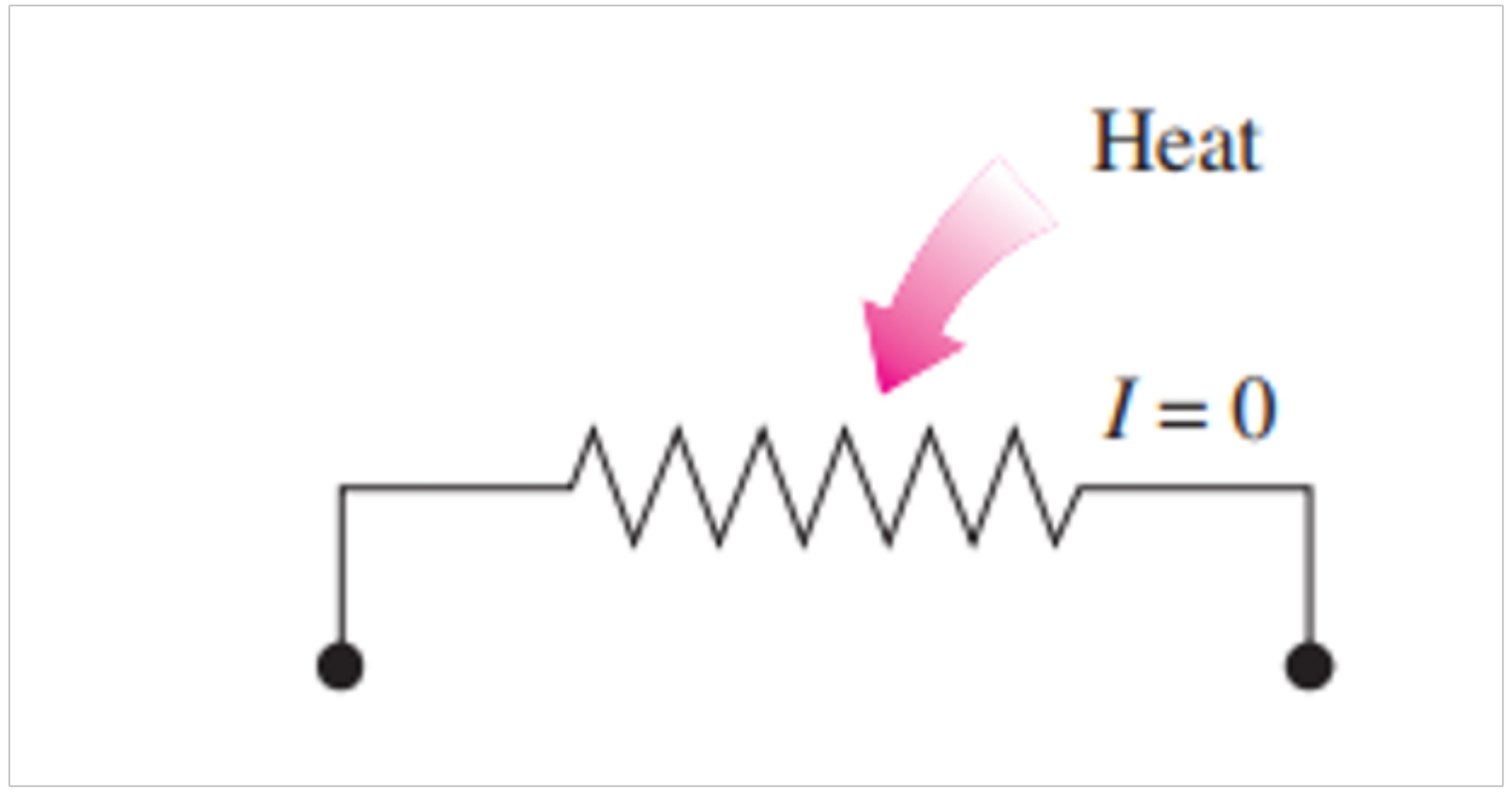
Direction dependence of energy transfer



The amount of energy lost by the coffee is equal to the amount gained by the surrounding air

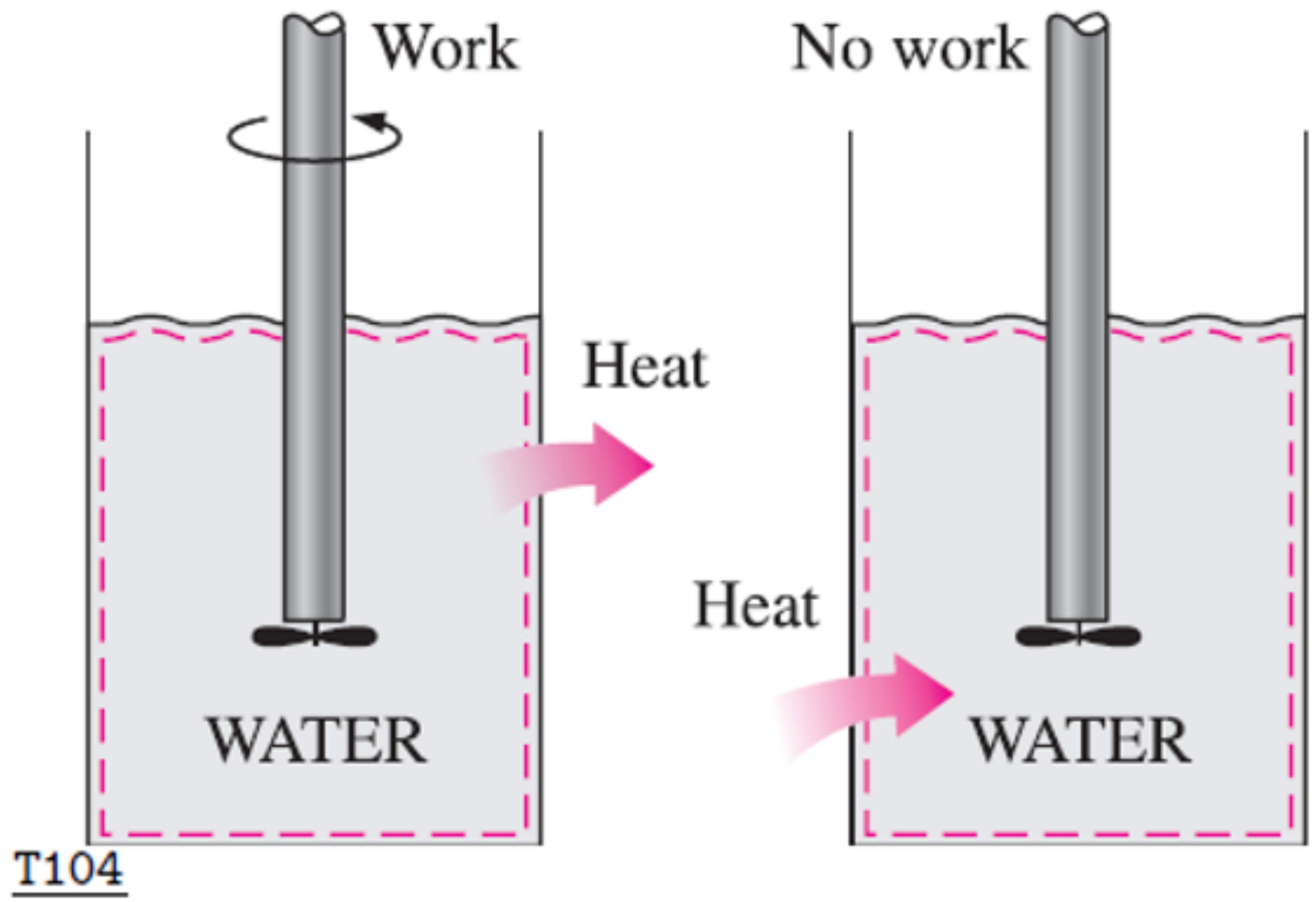
A cup of hot coffee does not get hotter in a cooler room.



The first law dictates that the amount of electric energy supplied to the resistance wires be equal to the amount of energy transferred to the room air as heat.

Transferring heat to a wire will not generate electricity.

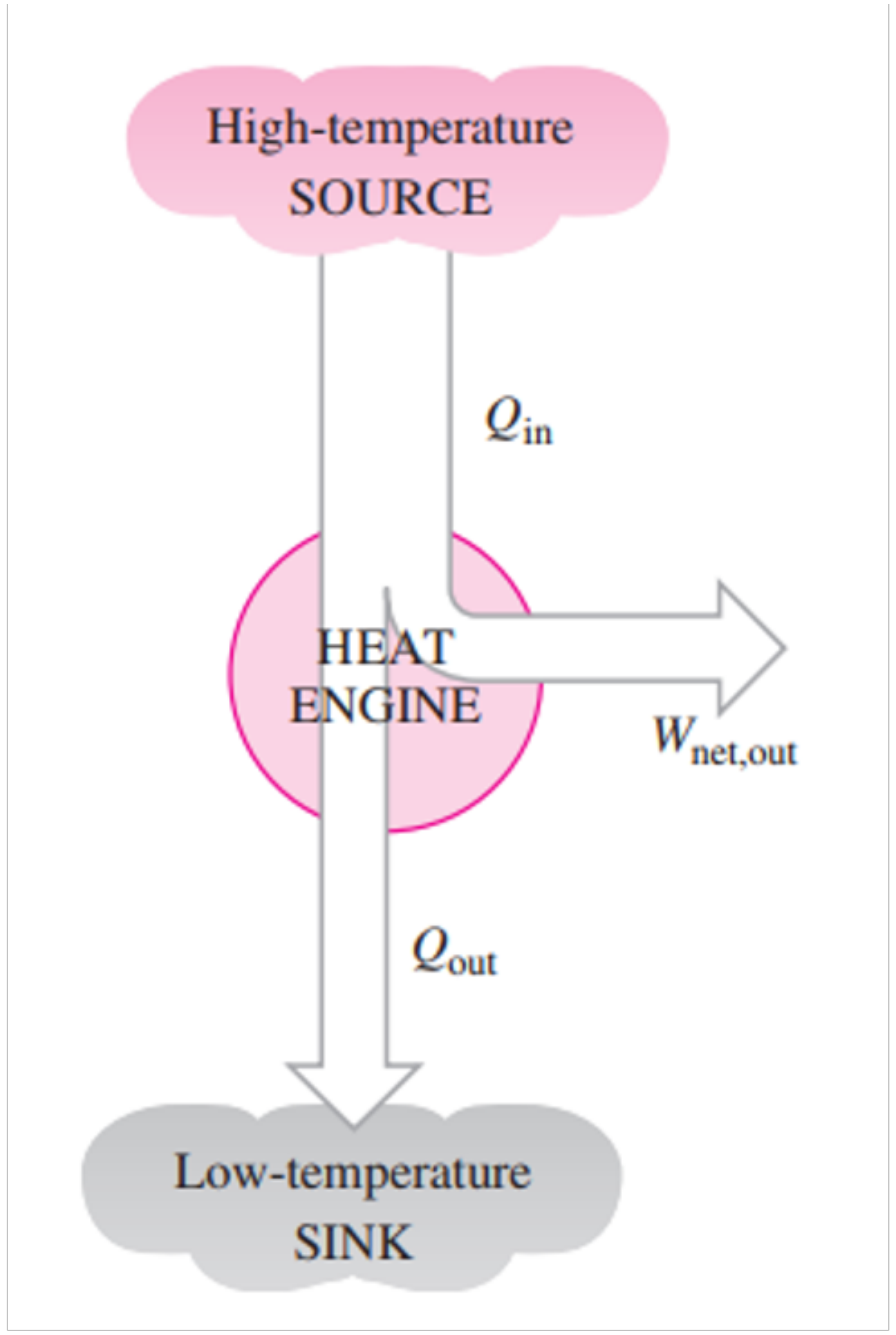
Some observation in work and heat conversions



Work can always be converted to heat directly and completely, but the reverse is not true.

- **Work can easily be converted to other forms of energy, but converting other forms of energy to work is not that easy**
- **Heat can be converted to work only by some devices called Heat Engines.**

Typical heat engine

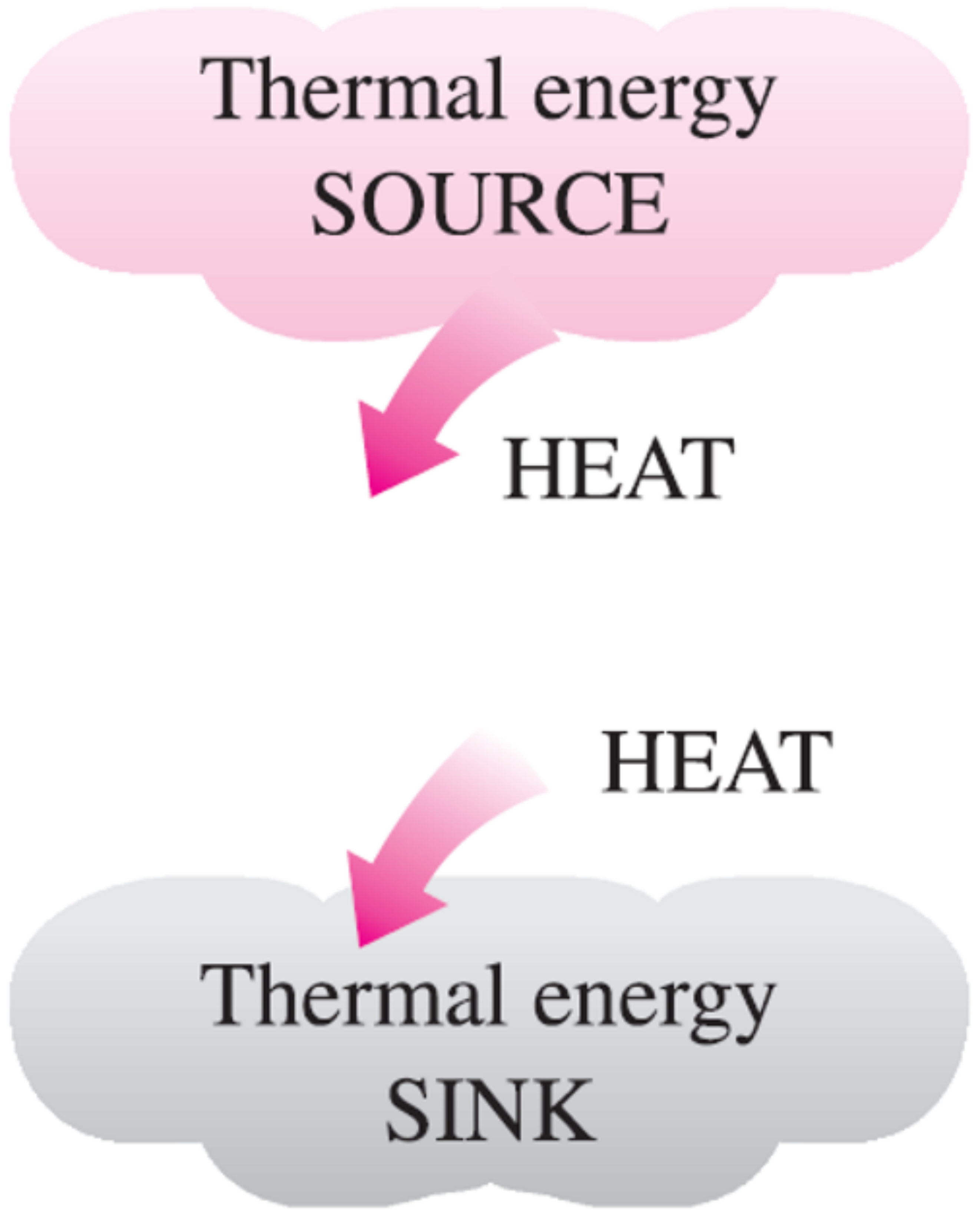


Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)
Q_{out} = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)
W_{out} = amount of work delivered by steam as it expands in turbine
W_{in} = amount of work required to compress water to boiler pressure

$$W_{net,out} = Q_{in} - Q_{out}$$

Thermal reservoir



A **thermal reservoir** is a closed system with the following characteristics:

- Temperature remains uniform and constant during a process.
- Changes within the thermal reservoir are internally reversible.
- Heat transfer to or from a thermal reservoir only results in an increase or decrease in the internal energy of the reservoir.

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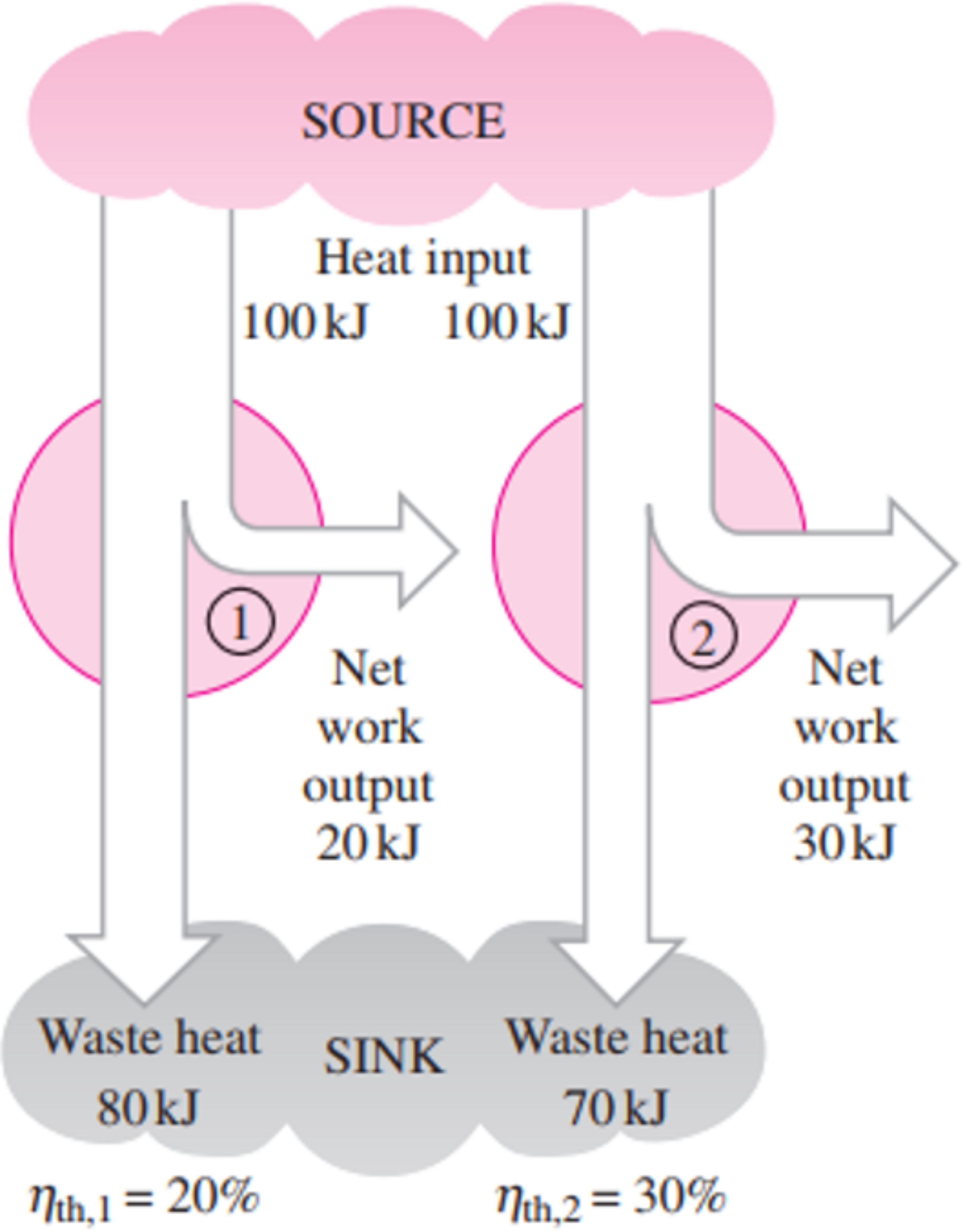
A thermal reservoir is an idealization which in practice can be closely approximated. Large bodies of water, such as oceans and lakes, and the atmosphere behave essentially as thermal reservoirs.

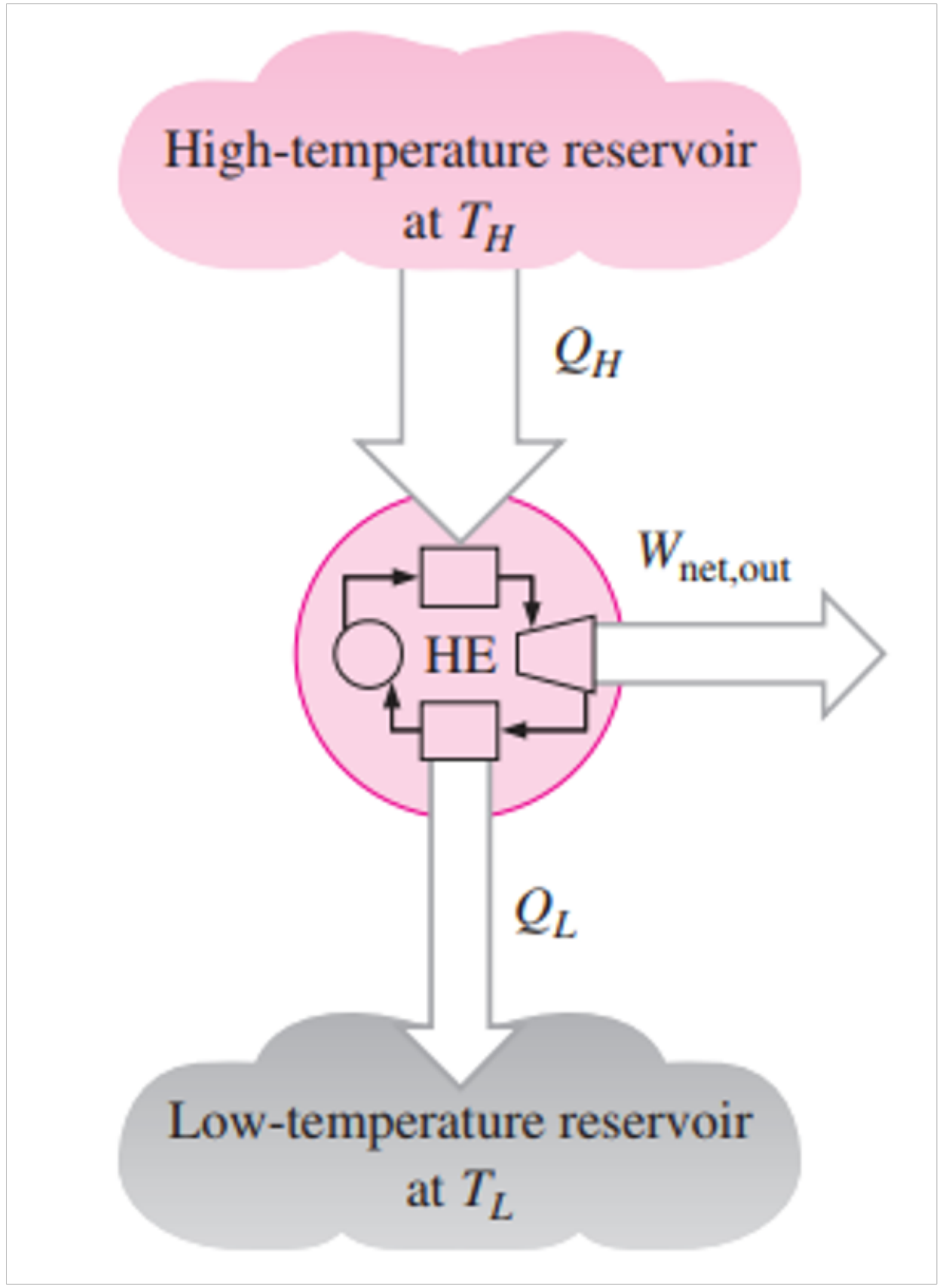
Thermal efficiency



$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

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

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

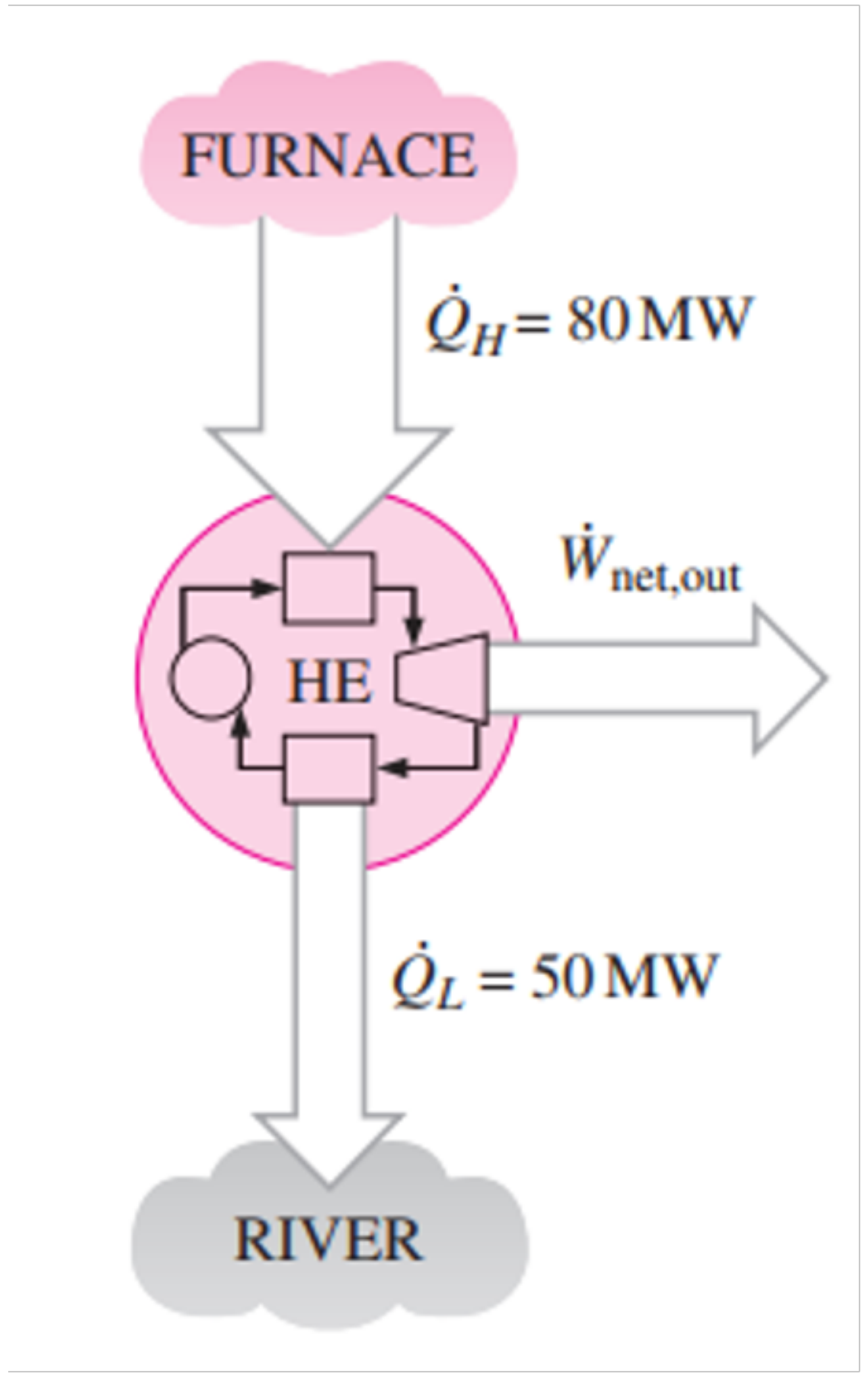


$$W_{net,out} = Q_H - Q_L$$

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

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

Example 1



EXAMPLE 6–1 Net Power Production of a Heat Engine

Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine the net power output and the thermal efficiency for this heat engine.

Solution The rates of heat transfer to and from a heat engine are given. The net power output and the thermal efficiency are to be determined.

Assumptions Heat losses through the pipes and other components are negligible.

Analysis A schematic of the heat engine is given in Fig. 6–16. The furnace serves as the high-temperature reservoir for this heat engine and the river as the low-temperature reservoir. The given quantities can be expressed as

$$\dot{Q}_H = 80 \text{ MW} \quad \text{and} \quad \dot{Q}_L = 50 \text{ MW}$$

The net power output of this heat engine is

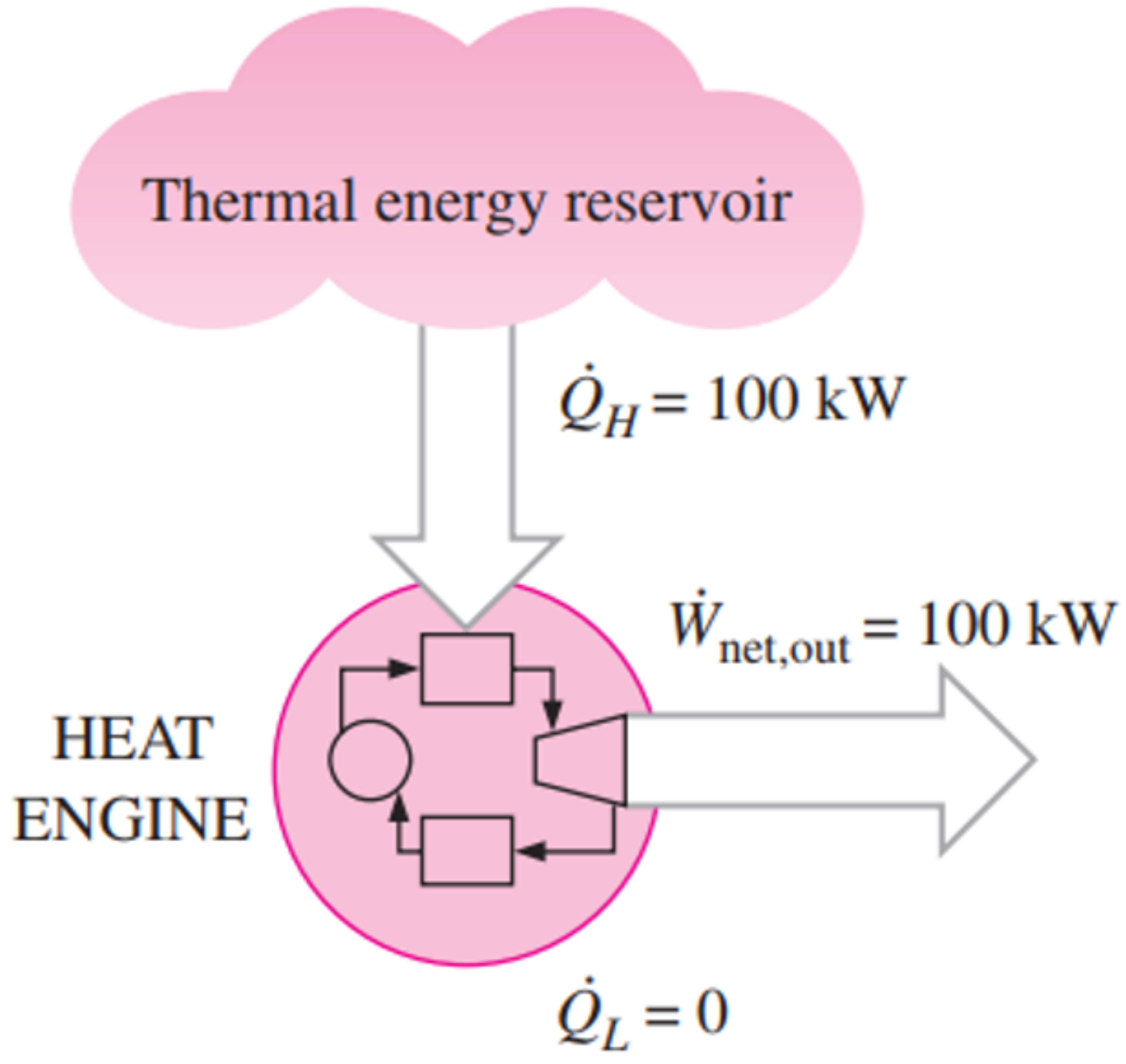
$$\dot{W}_{net,out} = \dot{Q}_H - \dot{Q}_L = (80 - 50) \text{ MW} = \mathbf{30\ MW}$$

Then the thermal efficiency is easily determined to be

$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_H} = \frac{30 \text{ MW}}{80 \text{ MW}} = \mathbf{0.375} \text{ (or } 37.5\%\text{)}$$

Kelvin-Planck (KP) statement

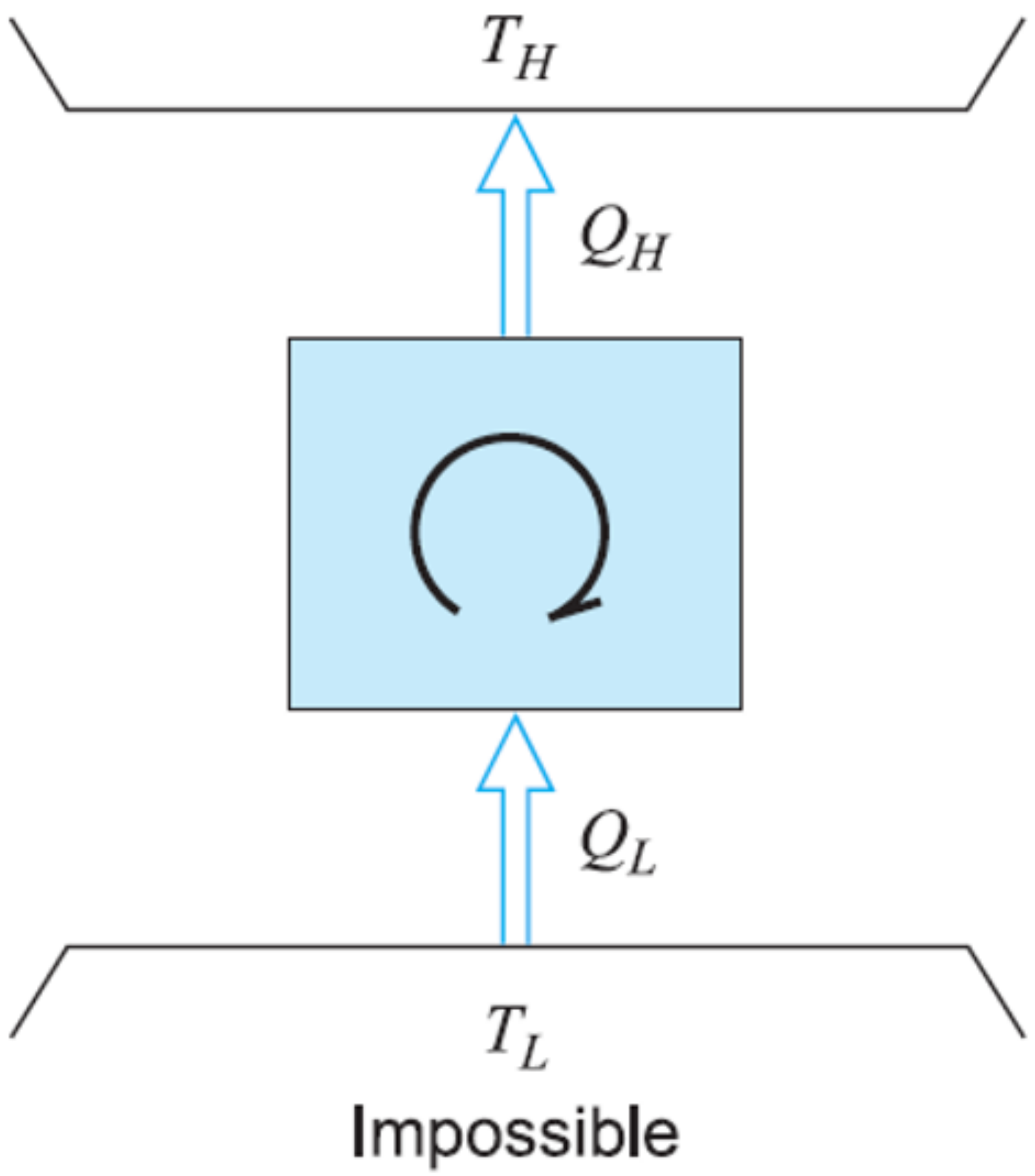
It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.



Clausius statement

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 cooler body to a hotter body.



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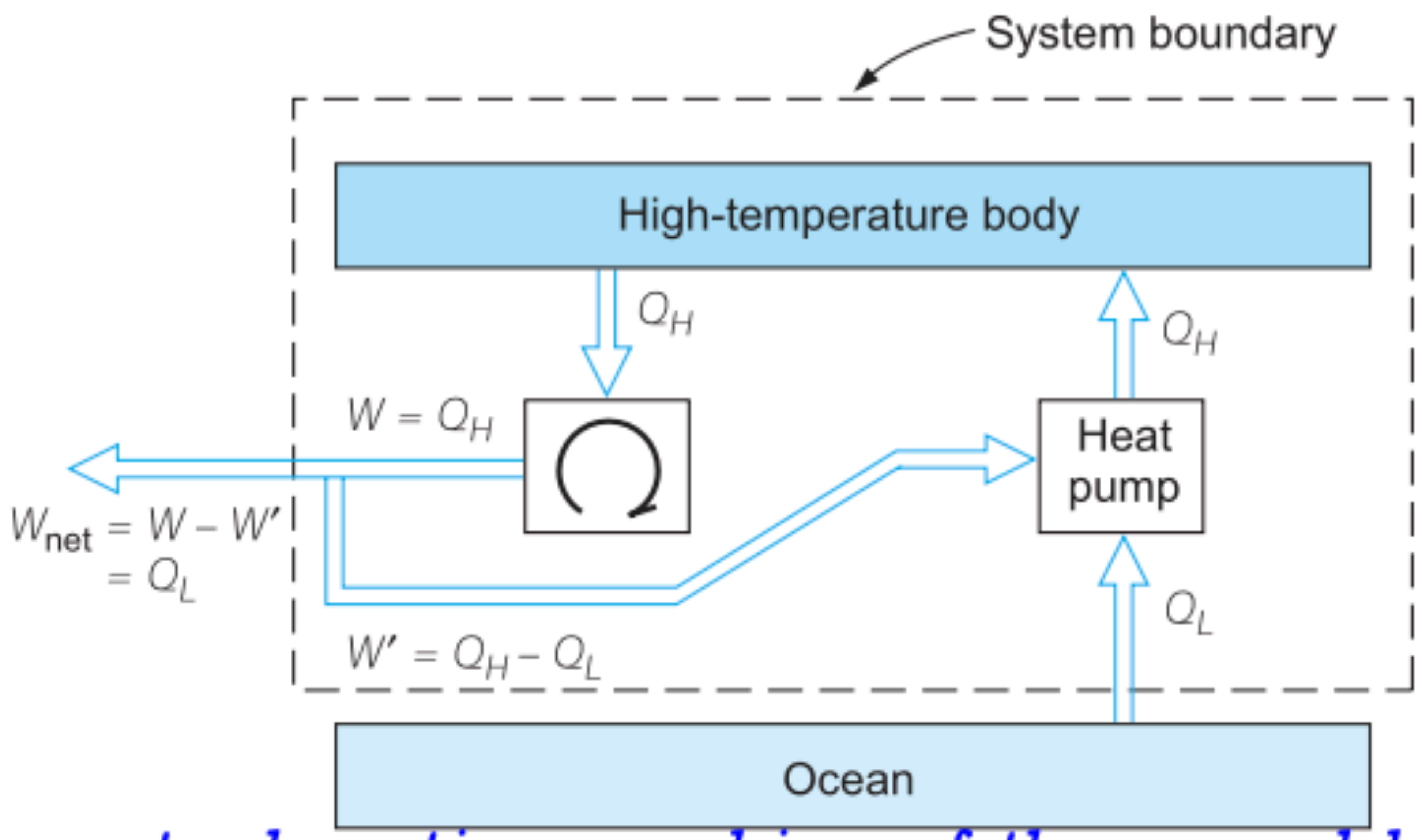
Related to Refrigeration Cycle

Three observations from the statements

1. Both are negative statements; negative statements are impossible to prove directly. Every relevant experiment that has been conducted, either directly or indirectly, verifies the second law, and no experiment has ever been conducted that contradicts the second law. The basis of the second law is therefore experimental evidence.
2. Both statements are equivalent. Two statements are equivalent if the truth of either statement implies the truth of the other or if the violation of either statement implies the violation of the other.
3. Both statements state the impossibility of Perpetual Motion Machine of 2nd Kind (PMM2).

Perpetual-motion machine (PMM)

1. A perpetual-motion machine of the first kind (PMM1) would create work from nothing or create mass or energy, thus violating the first law.
2. A perpetual-motion machine of the second kind (PMM2) would extract heat from a source and then convert this heat completely into other forms of energy, thus violating the second law.



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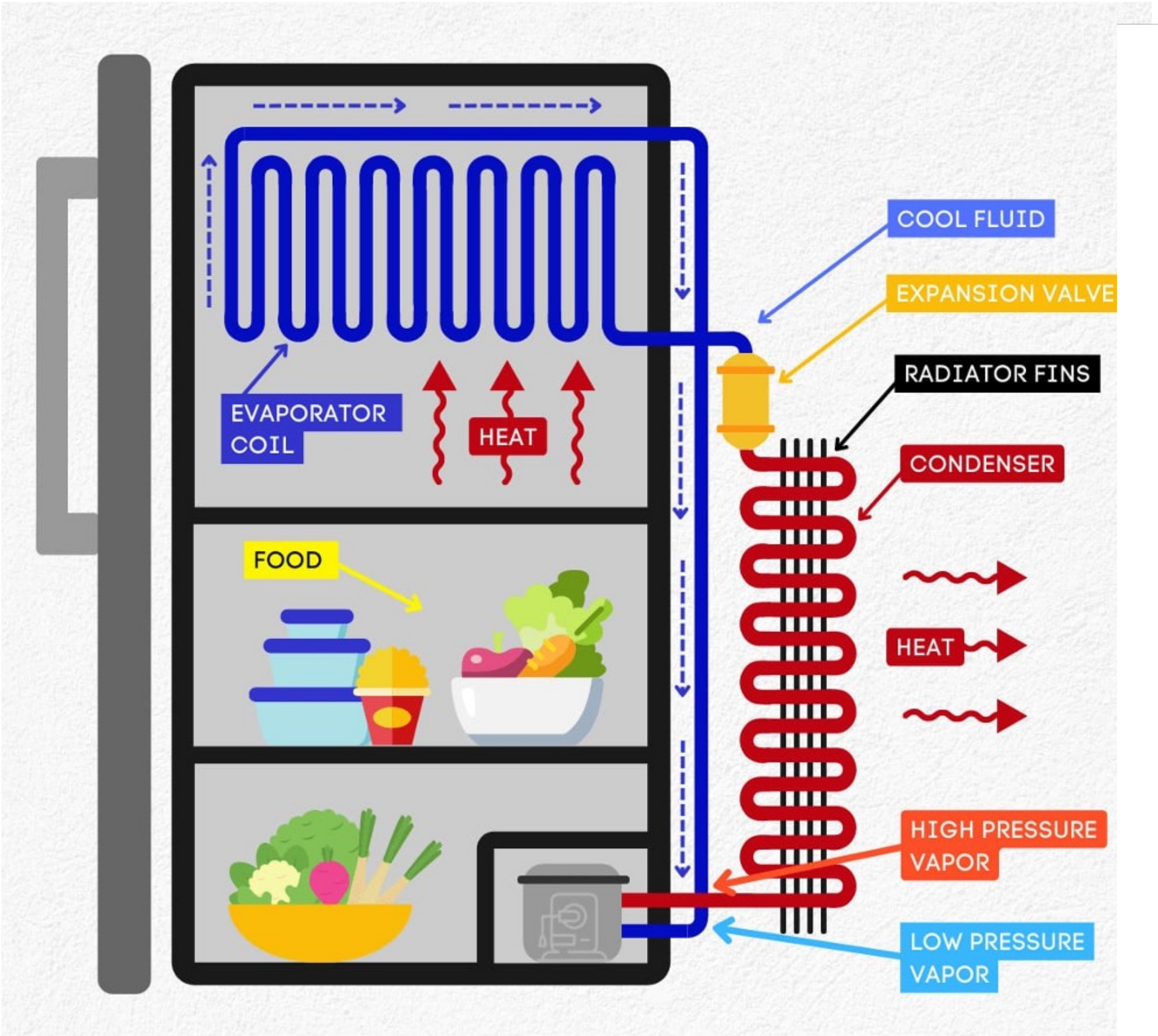
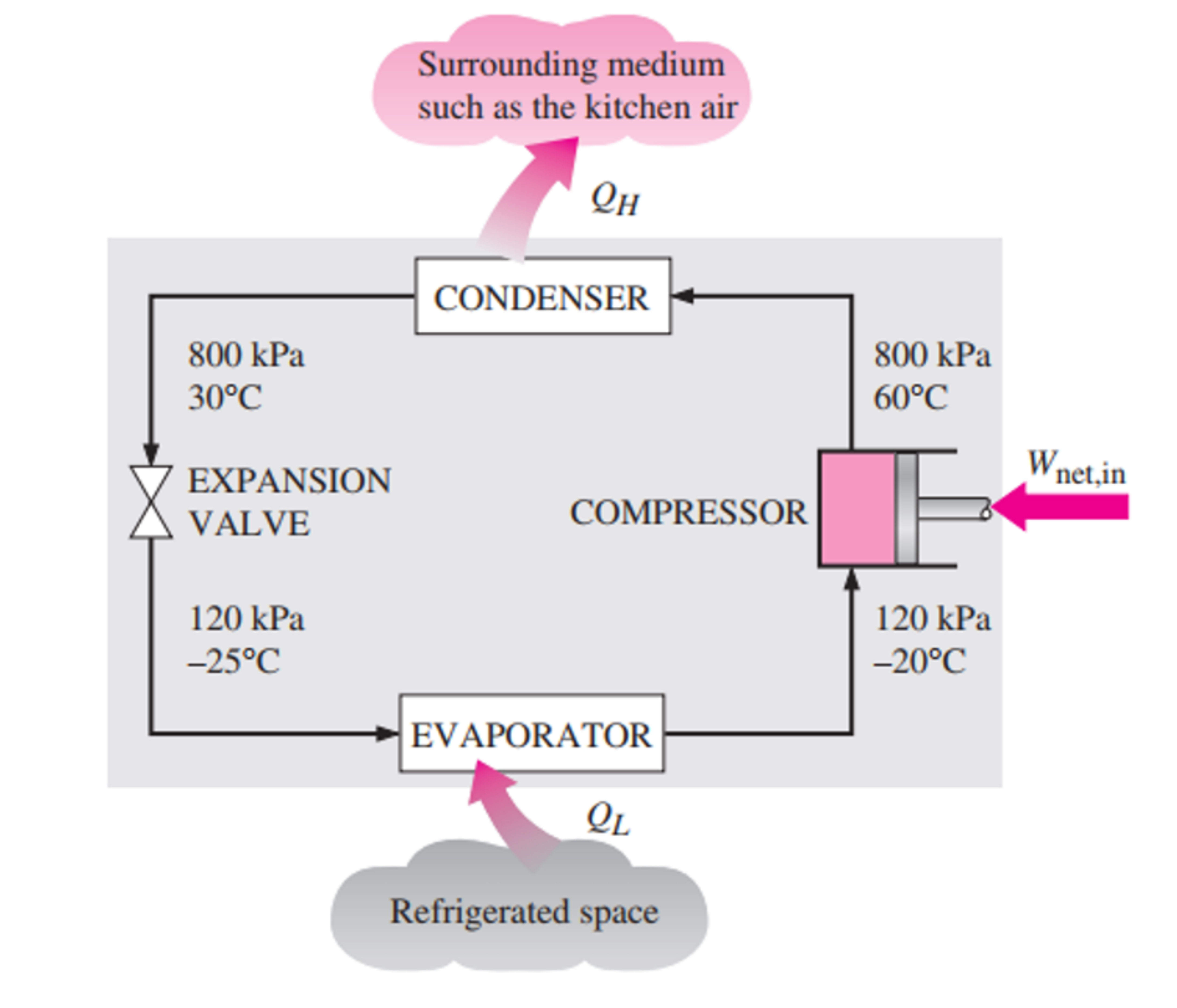
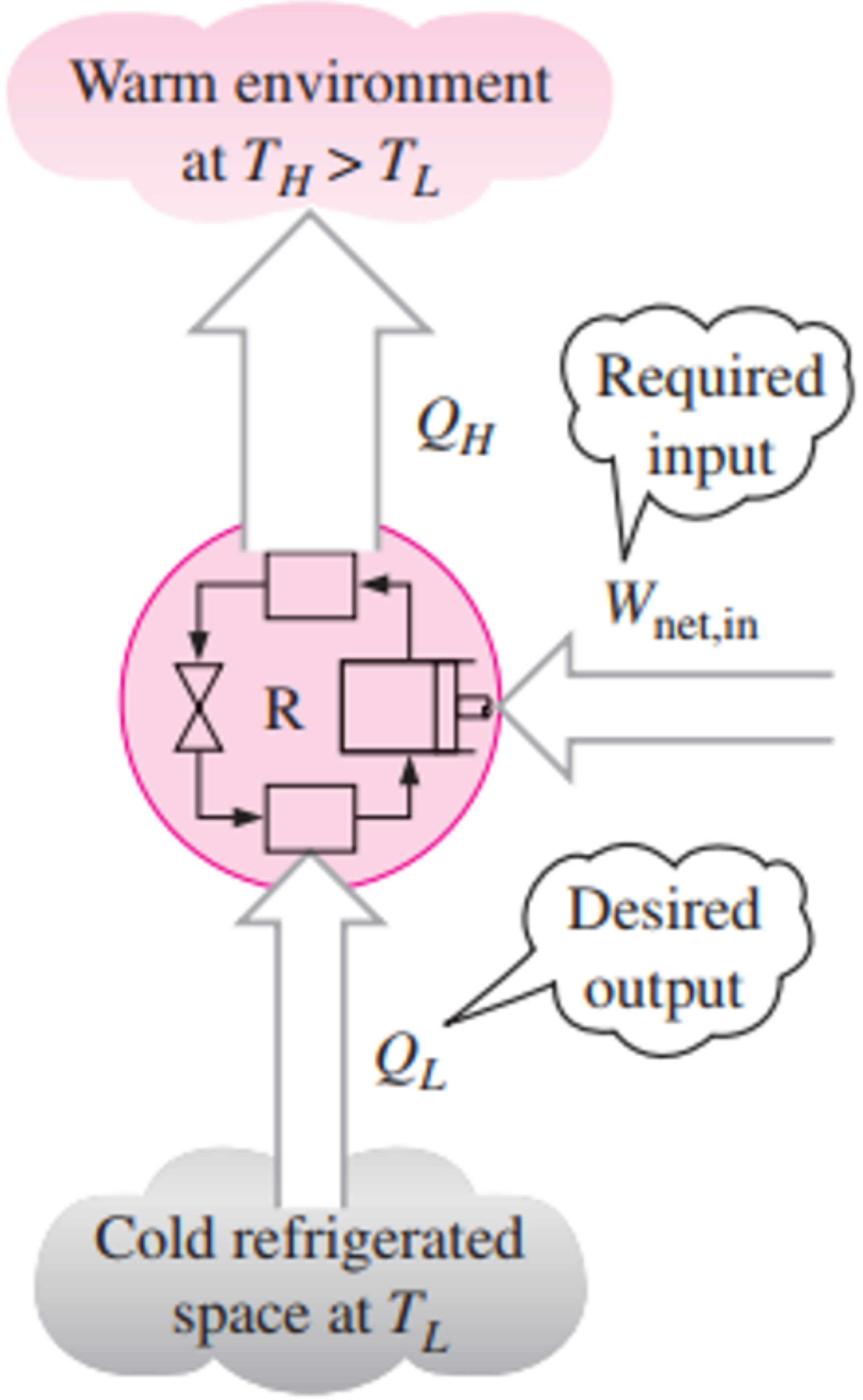
A perpetual-motion machine of the second kind.

Principle of a refrigeration cycle





COP



Coefficient of Performance

The *efficiency* of a refrigerator is expressed in terms of the **coefficient of performance** (COP), denoted by COP_R. The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space. To accomplish this objective, it requires a work input of $W_{net,in}$. Then the COP of a refrigerator can be expressed as

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{net,in}}$$

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

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

COP can be greater than 1

Example 2

EXAMPLE 6–3 Heat Rejection by a Refrigerator

The food compartment of a refrigerator, shown in Fig. 6–24, is maintained at 4°C by removing heat from it 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.

Solution The power consumption of a refrigerator is given. The COP and the rate of heat rejection are to be determined.

Assumptions Steady operating conditions exist.

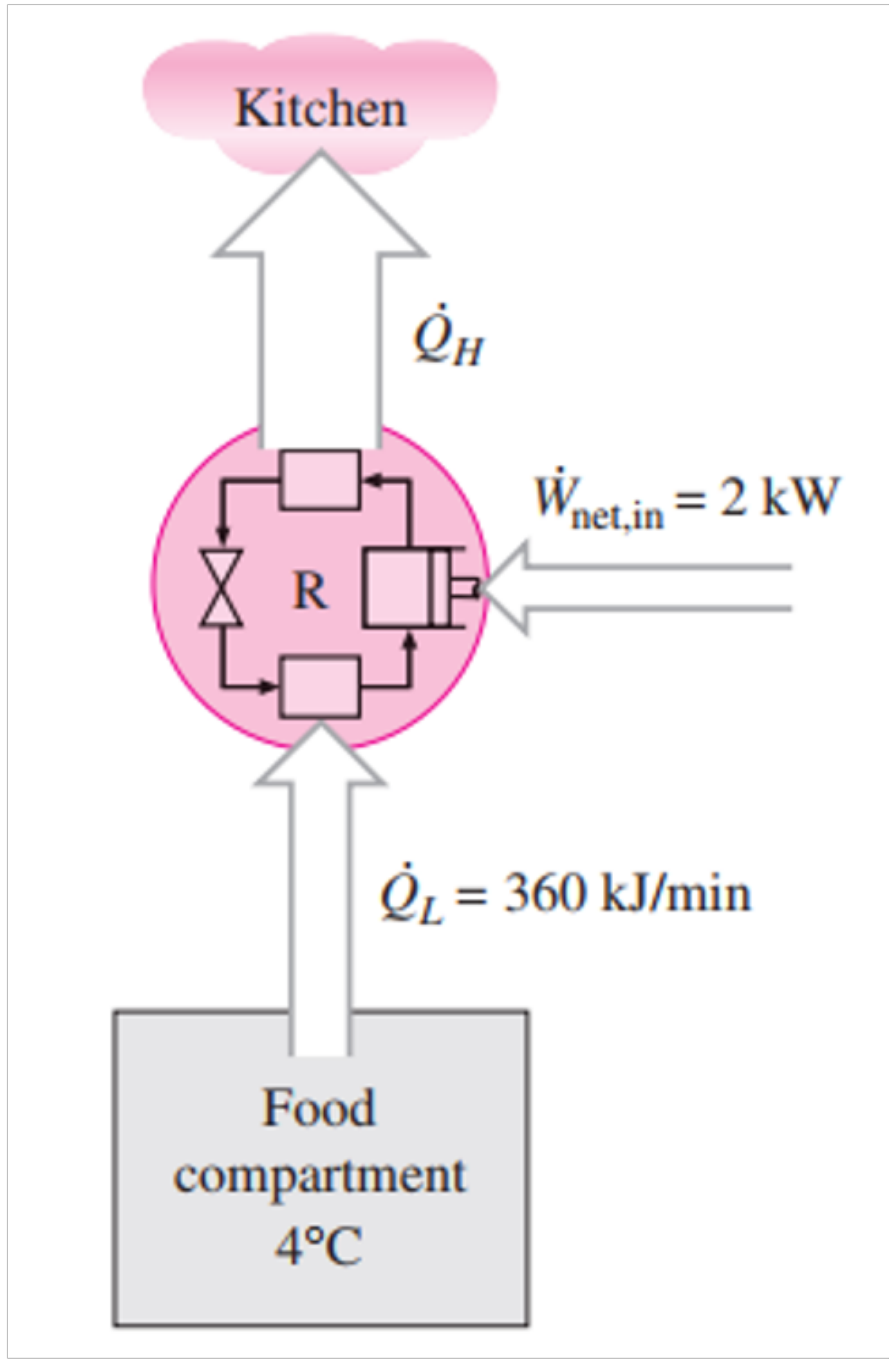
Analysis (*a*) The coefficient of performance of the refrigerator is

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{\text{net,in}}} = \frac{360 \text{ kJ/min}}{2 \text{ kW}}\left(\frac{1 \text{ kW}}{60 \text{ kJ/min}}\right) = 3$$

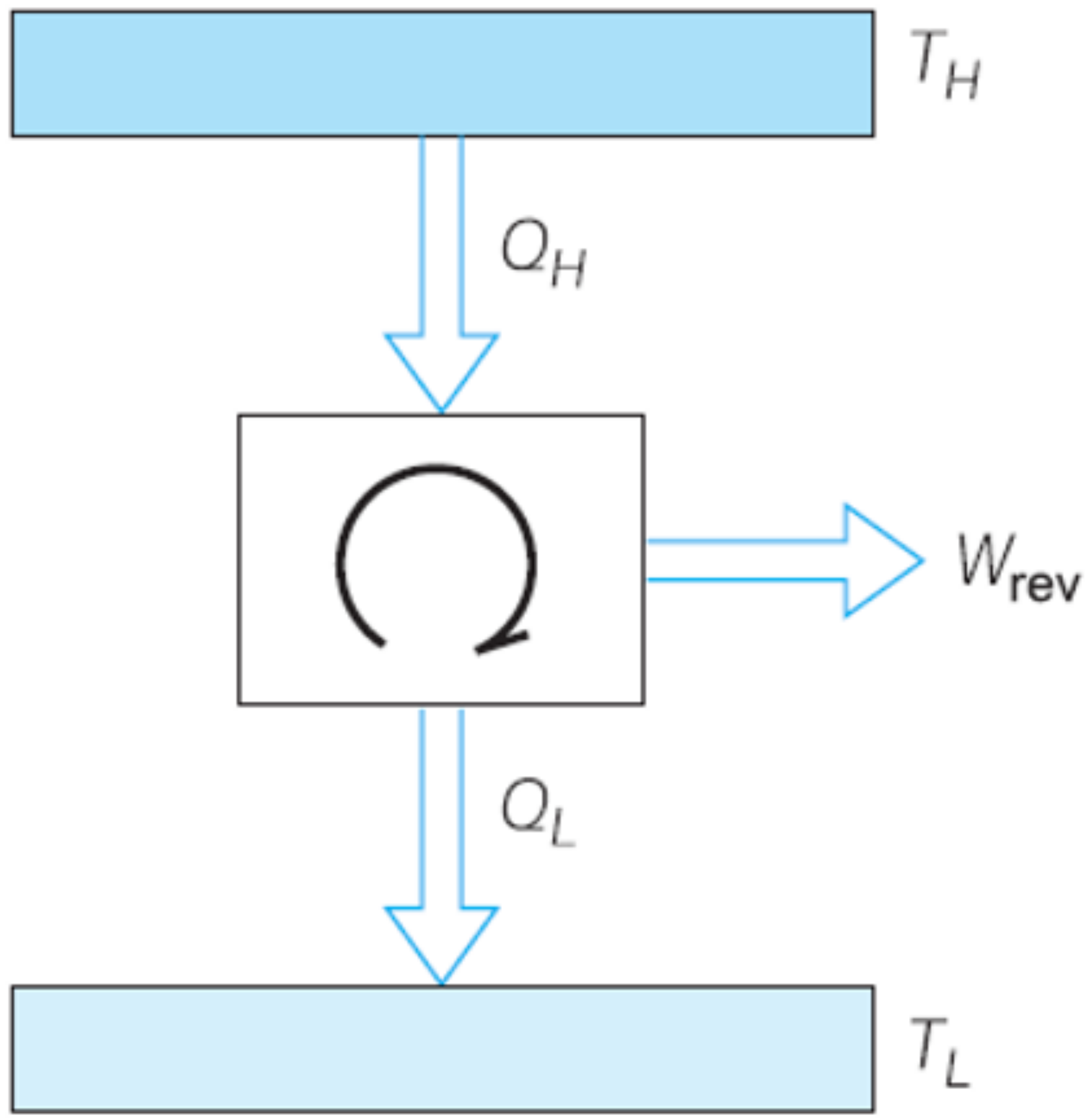
That is, 3 kJ of heat is removed from the refrigerated space for each kJ of work supplied.

(*b*) The rate at which heat is rejected to the room that houses the refrigerator is determined from the conservation of energy relation for cyclic devices,

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{\text{net,in}} = 360 \text{ kJ/min} + (2 \text{ kW})\left(\frac{60 \text{ kJ/min}}{1 \text{ kW}}\right) = 480 \text{ kJ/min}$$



Reversible engines



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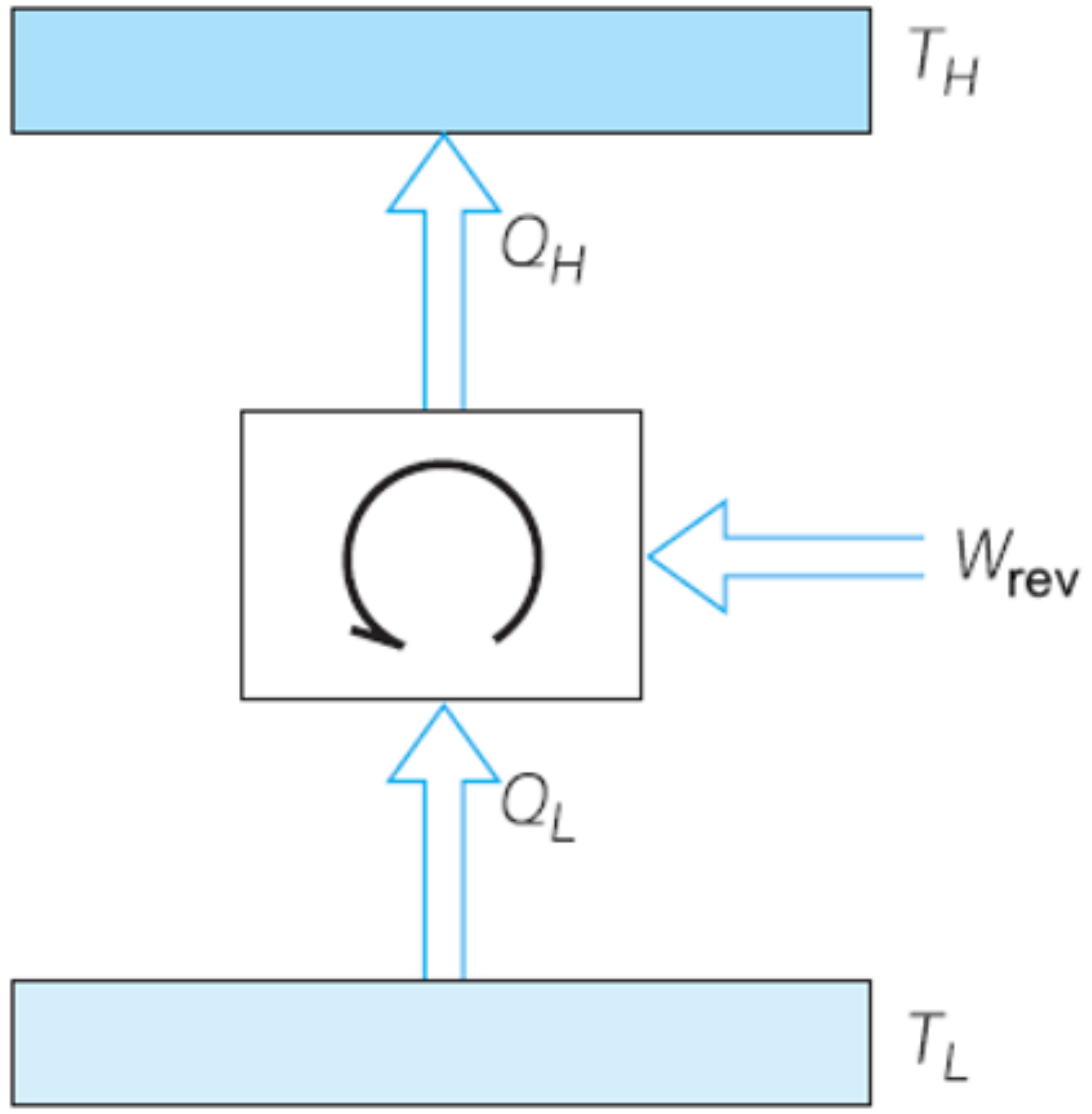

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- A **reversible process** for a system is defined as a process that once having taken place can be reversed and in so doing leave no change in either the system or the surrounding.
- A reversible power cycle can be changed to a reversible refrigeration cycle by just reversing all the heat and work flow quantities.

Revesible and irreversible process

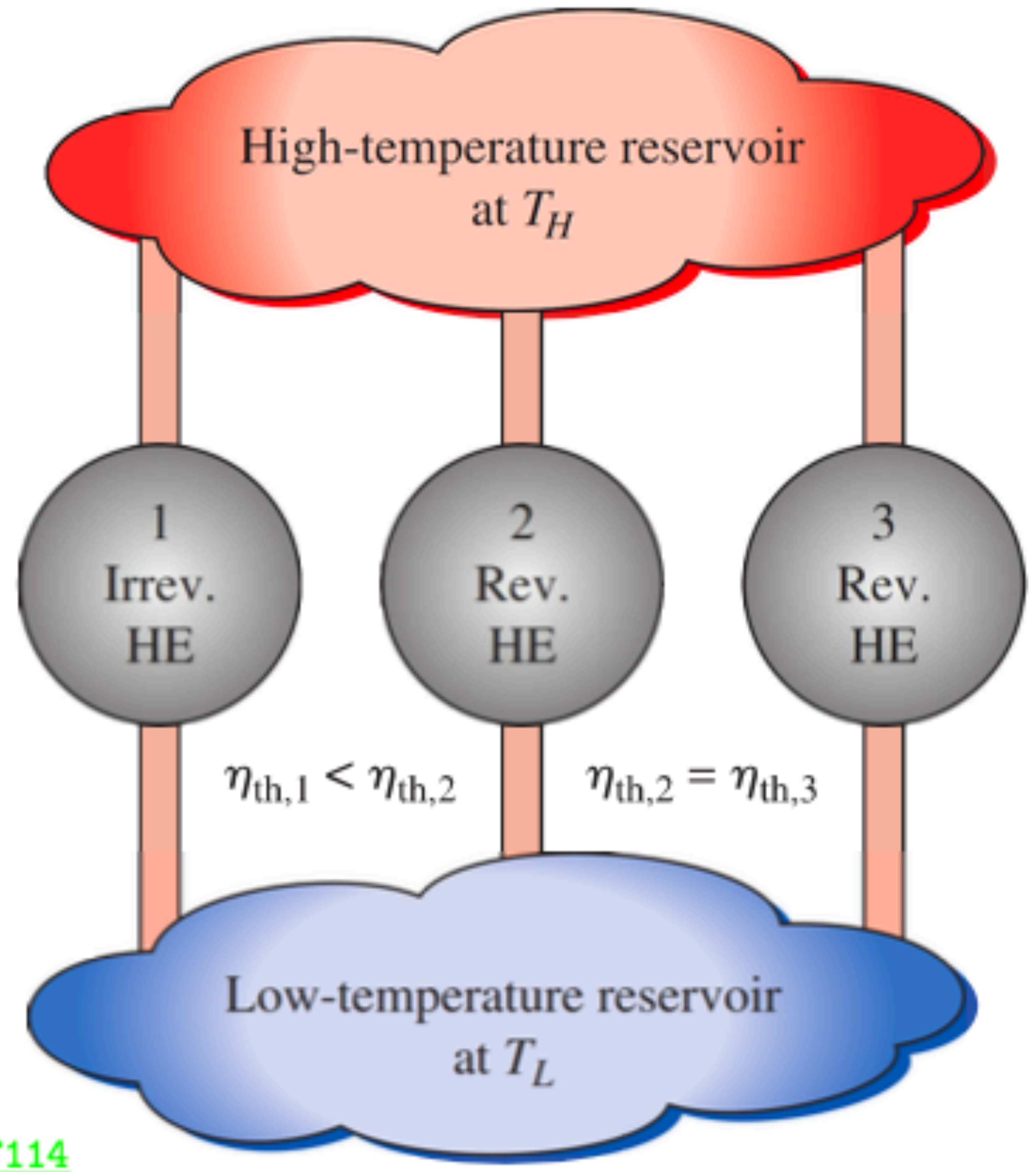
- A reversible process is defined as a *process that can be reversed without leaving any trace on the surroundings.* That is*, both the system and the surroundings are returned to their initial states at the end of the* reverse process. This is possible only if the net heat *and net work exchange* between the system and the surroundings is zero for the combined (original and reverse) process.
- Processes that are not reversible are called **irreversible processes.**
- The factors that cause a process to be irreversible are called **irreversibilities.**
- These include-
  1. Friction
  2. Unrestrained Expansion
  3. Mixing of two liquid
  4. Heat transfer across a finite temp. difference.
  5. Electric Resistance
  6. Inelastic deformation of solids
  7. Chemical Reactions etc.

Reversible process (internal, external, and total)

- A process is called **internally reversible if no irreversibilities occur** within the boundaries of the system during the process. During an internally reversible process, a system proceeds through a series of equilibrium states, and when the process is reversed, the system passes through exactly the same equilibrium states while returning to its initial state.
- A process is called **externally reversible if no irreversibilities occur outside** the system boundaries during the process. Heat transfer between a reservoir and a system is an externally reversible process if the outer surface of the system is at the temperature of the reservoir.
- A process is called **totally reversible, or simply reversible, if it involves** no irreversibilities within the system or its surroundings. A totally reversible process involves no heat transfer through a finite temperature difference, no nonquasi-equilibrium changes, and no friction or other dissipative effects.

Carnot principle

- It is impossible to construct an engine that operates between two given reservoirs and is more efficient than a reversible engine operating between the same two reservoirs.
- All engines that operate on the Carnot cycle between two given constant-temperature reservoirs have the same efficiency.



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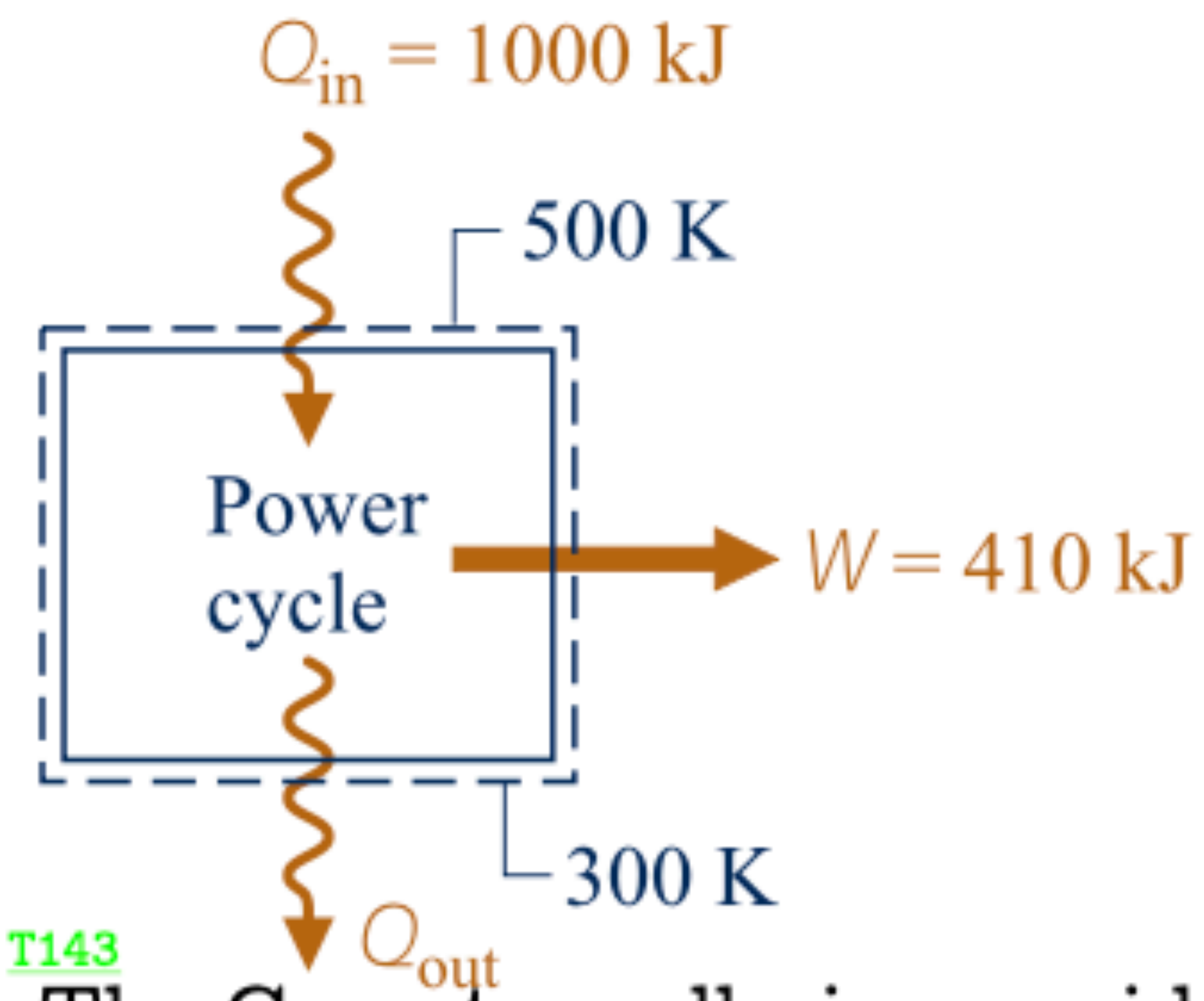
$$\eta_{th,rev} = 1 - \frac{Q_L}{Q_H} \approx 1 - \frac{T_L}{T_H}$$

- An absolute temperature scale may be defined which is independent of the measuring substances.

Example 3

Moran Ex. 5.1: ▷ An inventor claims to have developed a power cycle capable of delivering a net work output of 410 kJ for an energy input by heat transfer of 1000 kJ. The system undergoing the cycle receives the heat transfer from hot gases at a temperature of 500 K and discharges energy by heat transfer to the atmosphere at 300 K. Evaluate this claim.



- Claimed efficiency:

$$\Rightarrow \eta = \frac{W}{Q_{in}} = \frac{410}{1000} = 0.41 = 41\%.$$

- Maximum possible thermal efficiency:

$$\Rightarrow \eta_{max} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{500} = 0.40 = 40\%.$$

The Carnot corollaries provide a basis for evaluating the claim: Since the thermal efficiency of the actual cycle exceeds the maximum theoretical value, the claim cannot be valid.