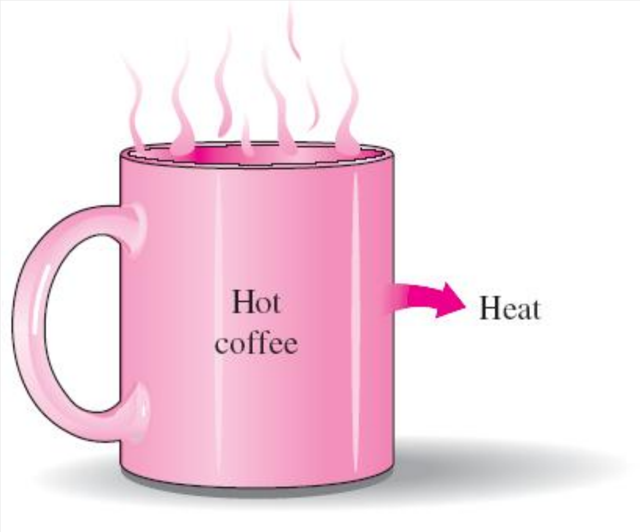
Chapter Five

THE SECOND LAW OF THERMODYNAMICS

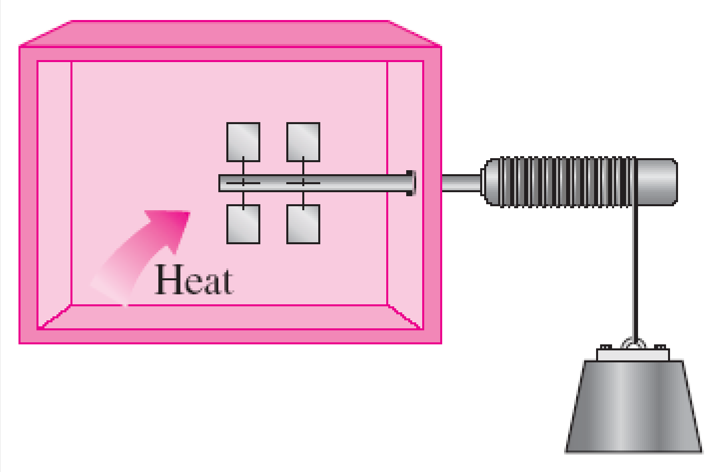
Objectives

- Introduce the second law of thermodynamics.
- Identify valid processes as those that satisfy both the first and second laws of thermodynamics.
- Discuss thermal energy reservoirs, reversible and irreversible processes, heat engines, refrigerators, and heat pumps.
- Describe the Kelvin–Planck and Clausius statements of the second law of thermodynamics.
- Apply the second law of thermodynamics to cycles and cyclic devices.
- Apply the second law to develop the absolute thermodynamic temperature scale.
- Describe the Carnot cycle.
- Examine the Carnot principles, idealized Carnot heat engines, refrigerators, and heat pumps.
- Determine the expressions for the thermal efficiencies and coefficients of performance for reversible heat engines, heat pumps, and refrigerators.

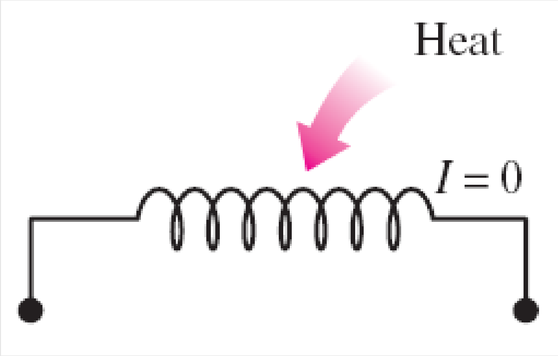
INTRODUCTION TO THE SECOND LAW



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



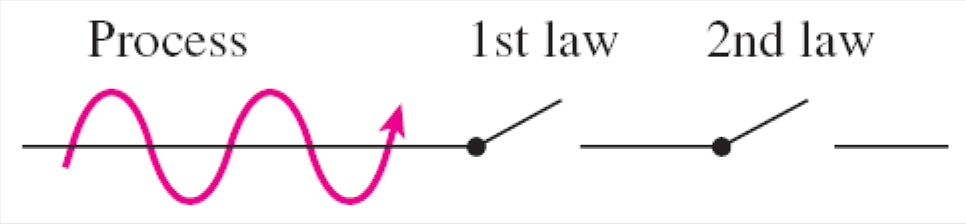
Transferring heat to a paddle wheel will not cause it to rotate.



Transferring heat to a wire will not generate electricity.

These processes cannot occur even though they are not in violation of the first law.

Processes occur in a certain direction, and not in the reverse direction.

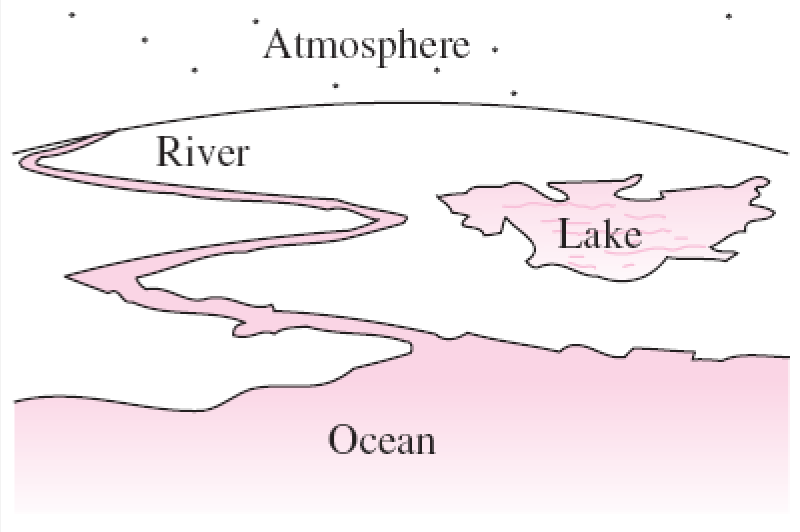


A process must satisfy both the first and second laws of thermodynamics to proceed.

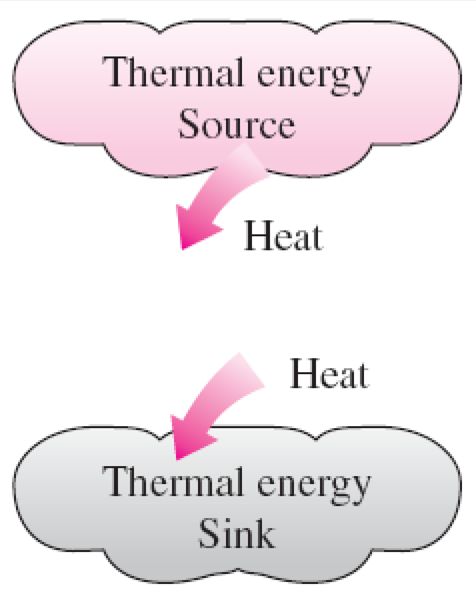
MAJOR USES OF THE SECOND LAW

1. The second law may be used to identify the direction of processes.
2. The second law also asserts that energy has *quality* as well as quantity. The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality. The second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process.
3. The second law of thermodynamics is also used in determining the *theoretical limits* for the performance of commonly used engineering systems, such as heat engines and refrigerators, as well as predicting the *degree of completion* of chemical reactions.

THERMAL ENERGY RESERVOIRS



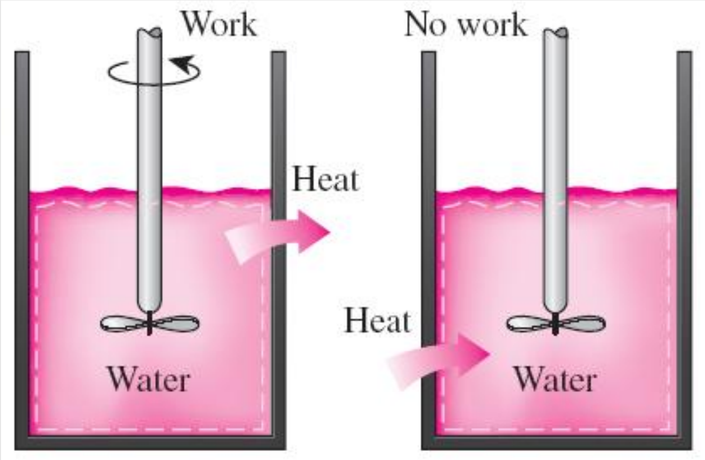
Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs.

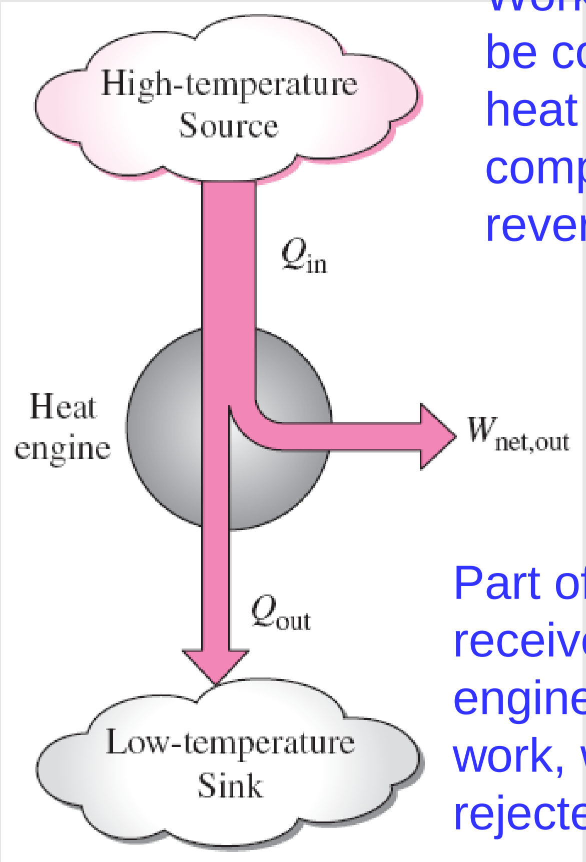


A **source** supplies energy in the form of heat, and a **sink** absorbs it.

- A hypothetical body with a relatively large *thermal energy capacity* (mass x specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature is called a **thermal energy reservoir**, or just a reservoir.
- In practice, large bodies of water such as oceans, lakes, and rivers as well as the atmospheric air can be modeled accurately as thermal energy reservoirs because of their large thermal energy storage capabilities or thermal masses.

HEAT ENGINES





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

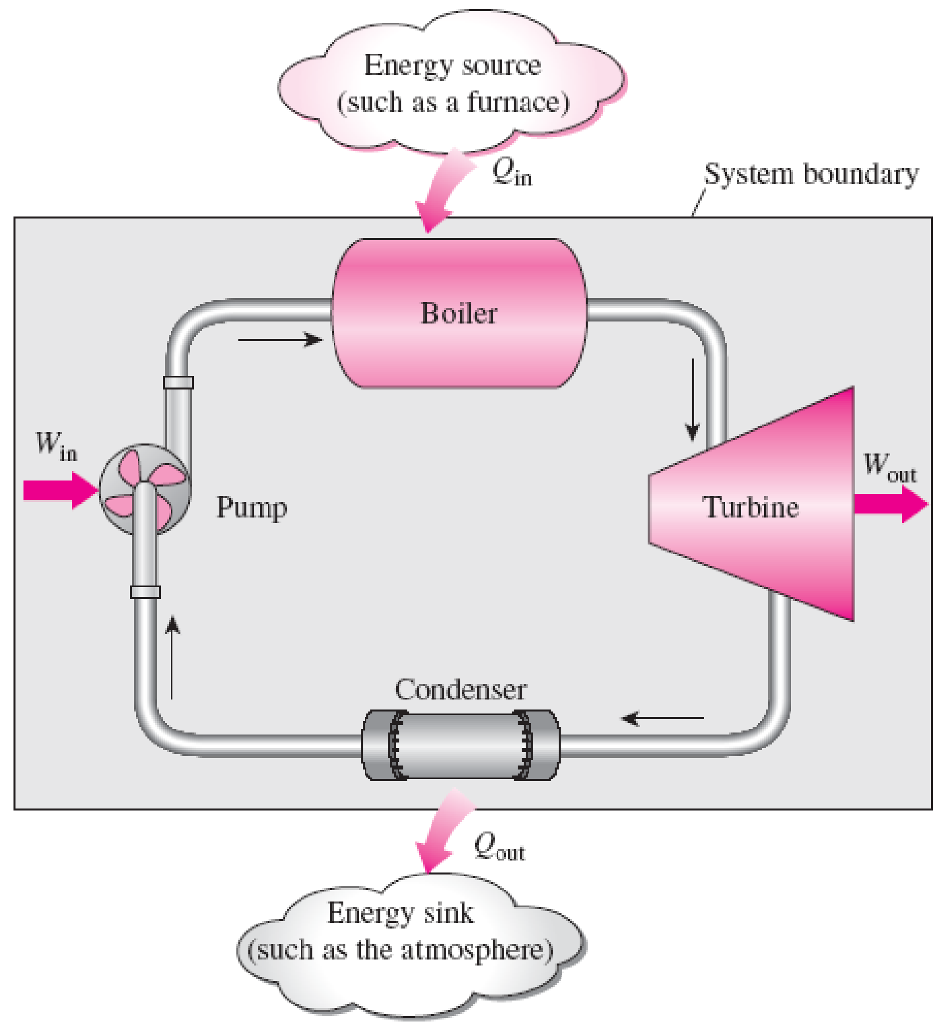
Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

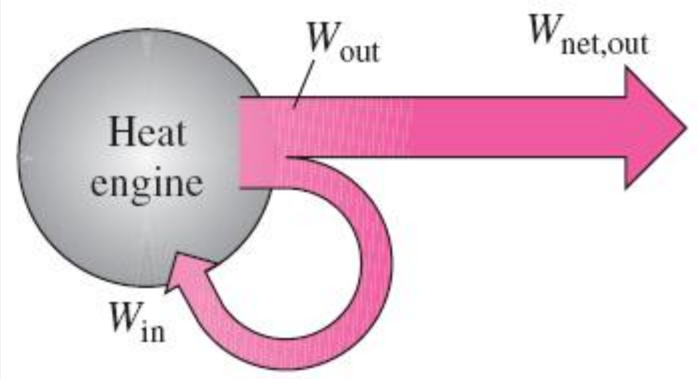
The devices that convert heat to work.

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.

Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the **working fluid**.

A steam power plant





A portion of the work output of a heat engine is consumed internally to maintain continuous operation.

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

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

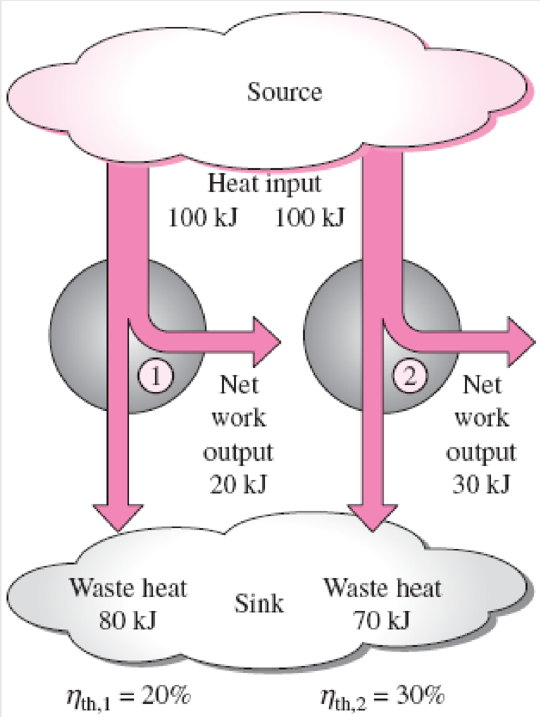
Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)

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

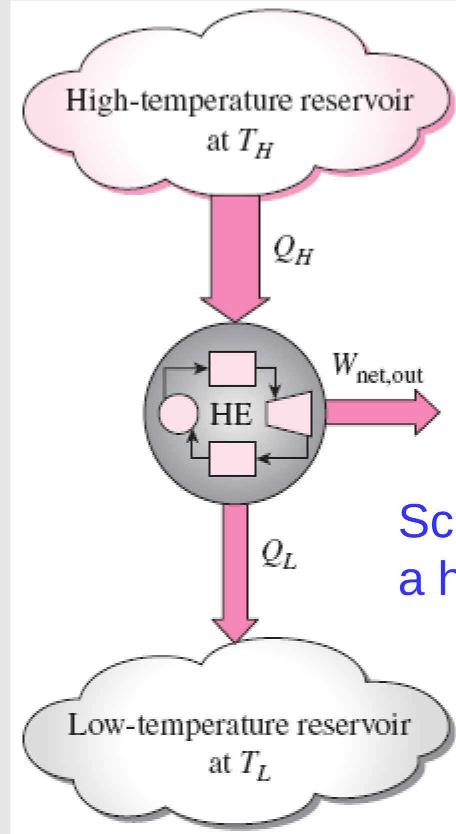
W_{out} = amount of work delivered by steam as it expands in turbine

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

Thermal efficiency



Some heat engines perform better than others (convert more of the heat they receive to work).

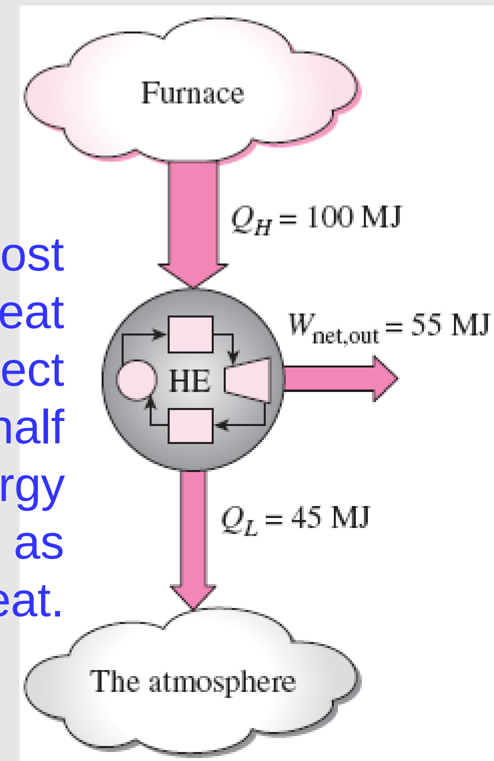


$$W_{net,out} = Q_H - Q_L$$

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

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

Schematic of a heat engine.



Even the most efficient heat engines reject almost one-half of the energy they receive as waste heat.

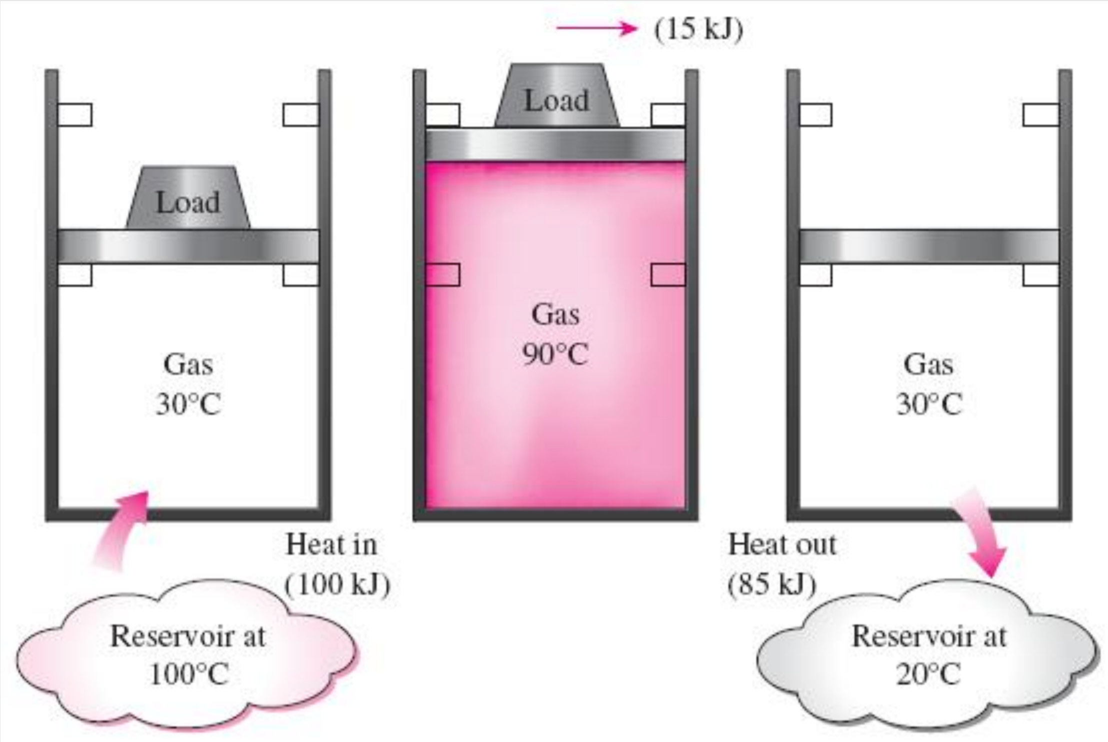
$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

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

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

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

Can we save Q_{out}?



A heat-engine cycle cannot be completed without rejecting some heat to a low-temperature sink.

Every heat engine must *waste* some energy by transferring it to a low-temperature reservoir in order to complete the cycle, even under idealized conditions.

In a steam power plant, the condenser is the device where large quantities of waste heat is rejected to rivers, lakes, or the atmosphere.

Can we not just take the condenser out of the plant and save all that waste energy?

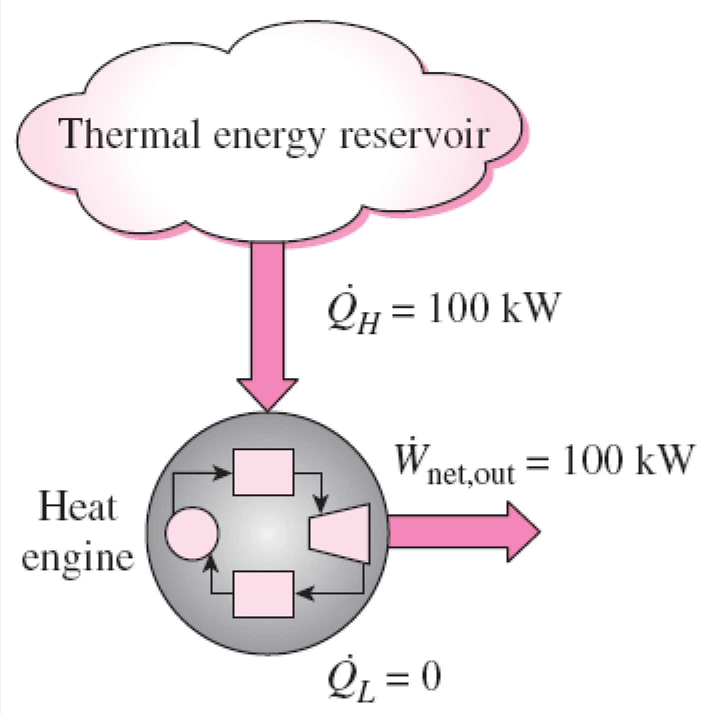
The answer is, unfortunately, a firm ***no*** for the simple reason that without a heat rejection process in a condenser, the cycle cannot be completed.

The Second Law of Thermodynamics: Kelvin–Planck 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.

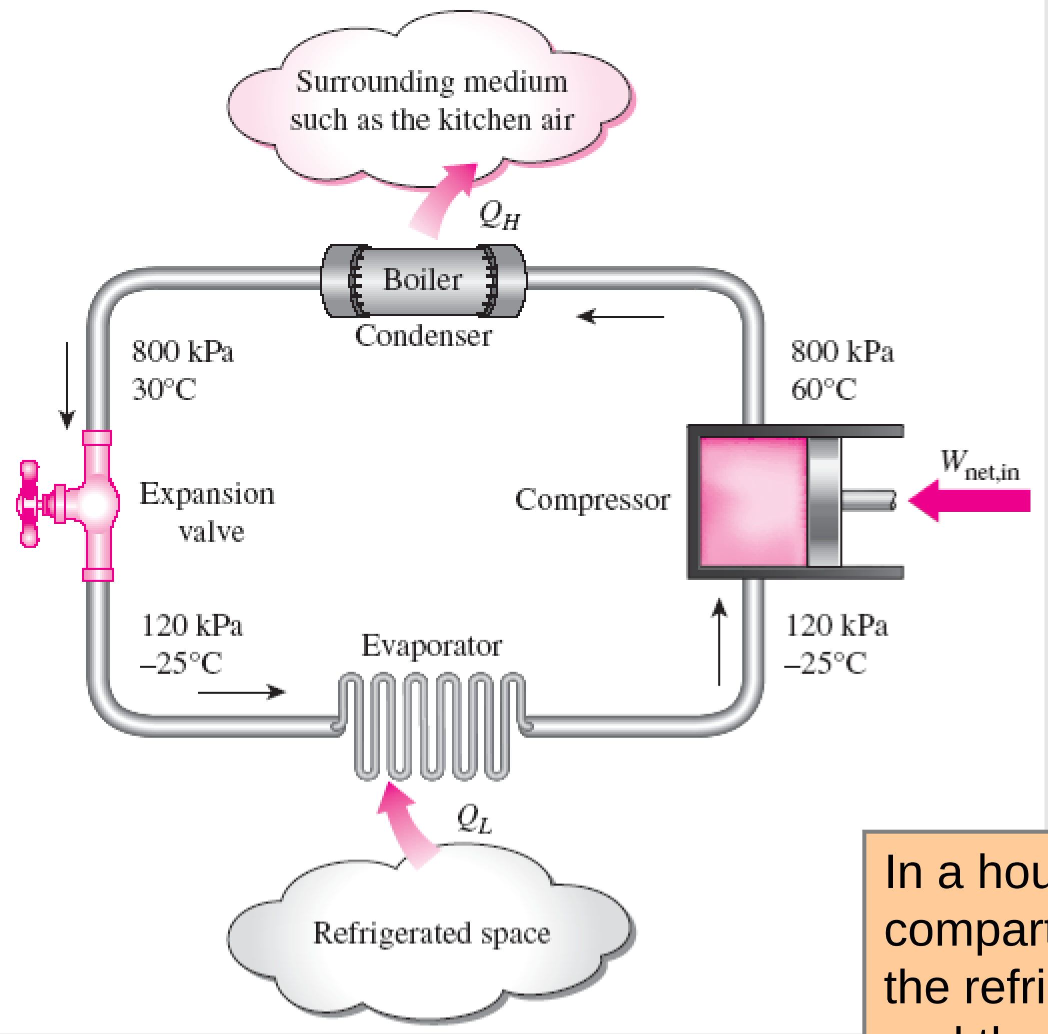
No heat engine can have a thermal efficiency of 100 percent, or *as for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace*.

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.



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

REFRIGERATORS AND HEAT PUMPS



Basic components of a refrigeration system and typical operating conditions.

The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called **refrigerators**.

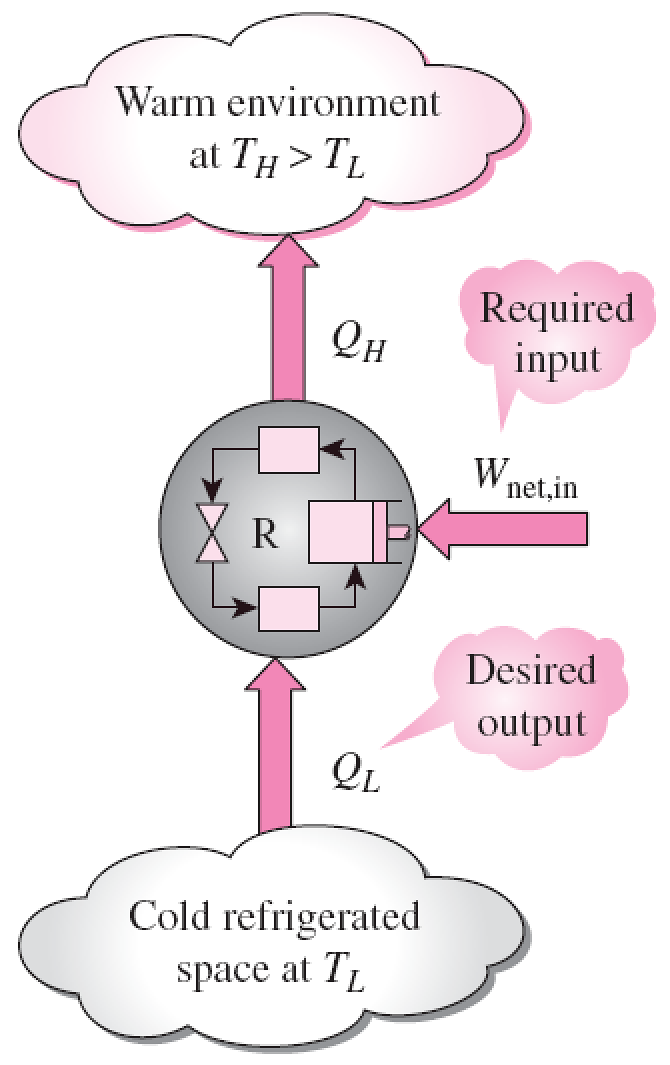
Refrigerators, like heat engines, are cyclic devices.

The working fluid used in the refrigeration cycle is called a **refrigerant**.

The most frequently used refrigeration cycle is the ***vapor-compression refrigeration cycle***.

In a household refrigerator, the freezer compartment where heat is absorbed by the refrigerant serves as the evaporator, and the coils usually behind the refrigerator where heat is dissipated to the kitchen air serve as the condenser.

Coefficient of Performance



The objective of a refrigerator is to remove Q_L from the cooled space.

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.

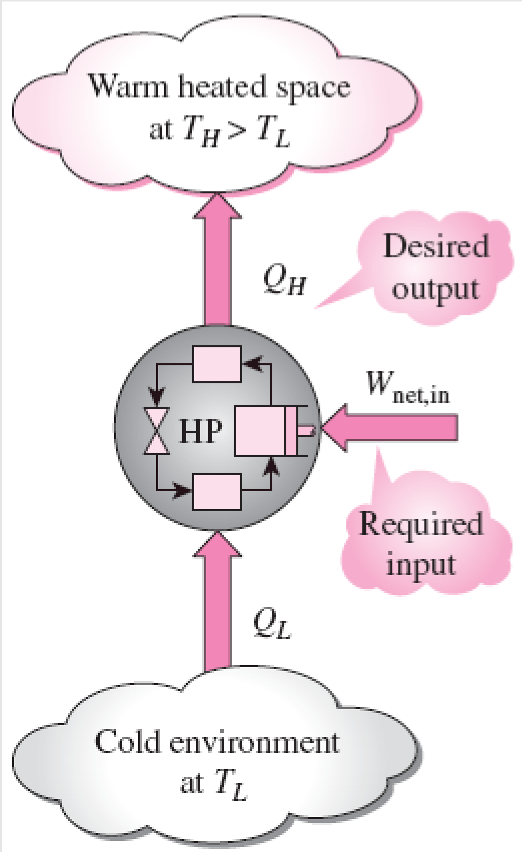
$$\text{COP}_\text{R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{\text{net,in}}}$$

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

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

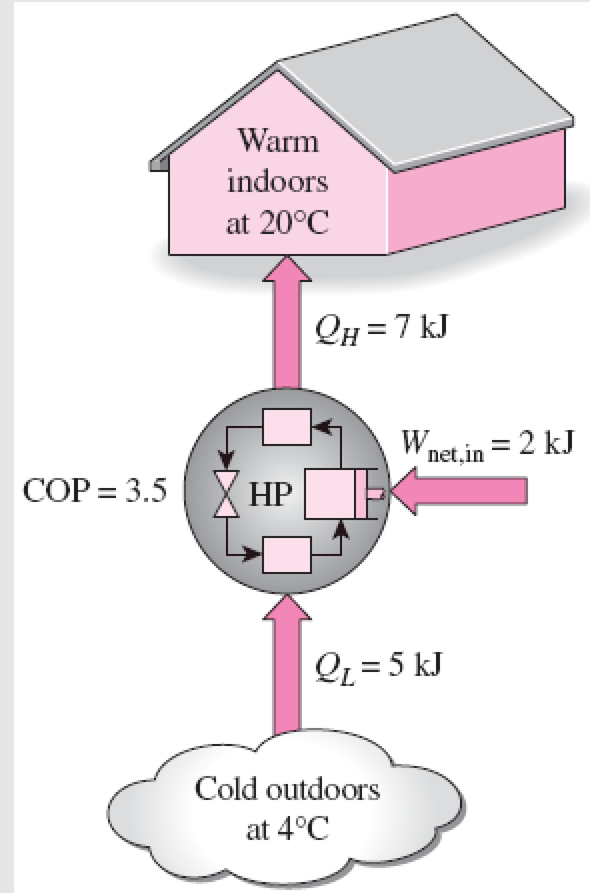
Can the value of COP_R be greater than unity?

Heat Pumps



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

The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.



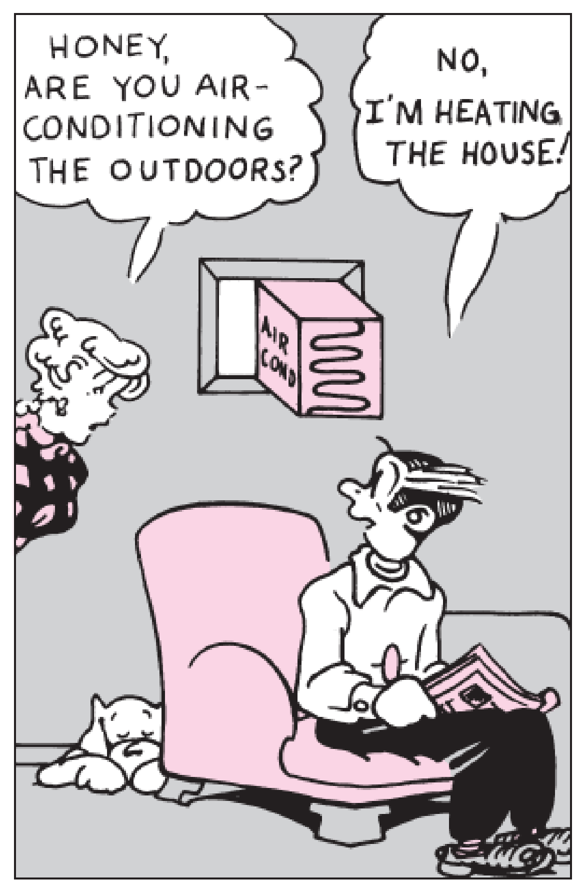
$$\mathrm{COP_{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{net,in}}$$

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

$\mathrm{COP_{HP}} = \mathrm{COP_R} + 1$ for fixed values of Q_L and Q_H

Can the value of $\mathrm{COP_{HP}}$ be lower than unity?

What does $\mathrm{COP_{HP}}=1$ represent?



When installed backward, an air conditioner functions as a heat pump.

- Most heat pumps in operation today have a seasonally averaged COP of 2 to 3.
- Most existing heat pumps use the cold outside air as the heat source in winter (*air-source* HP).
- In cold climates their efficiency drops considerably when temperatures are below the freezing point.
- In such cases, *geothermal* (*ground-source*) HP that use the ground as the heat source can be used.
- Such heat pumps are more expensive to install, but they are also more efficient.
- **Air conditioners** are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment.
- The COP of a refrigerator decreases with decreasing refrigeration temperature.
- Therefore, it is not economical to refrigerate to a lower temperature than needed.

Energy efficiency rating (EER): The amount of heat removed from the cooled space in Btu's for 1 Wh (watthour) of electricity consumed.

$$EER \equiv 3.412\ COP_R$$

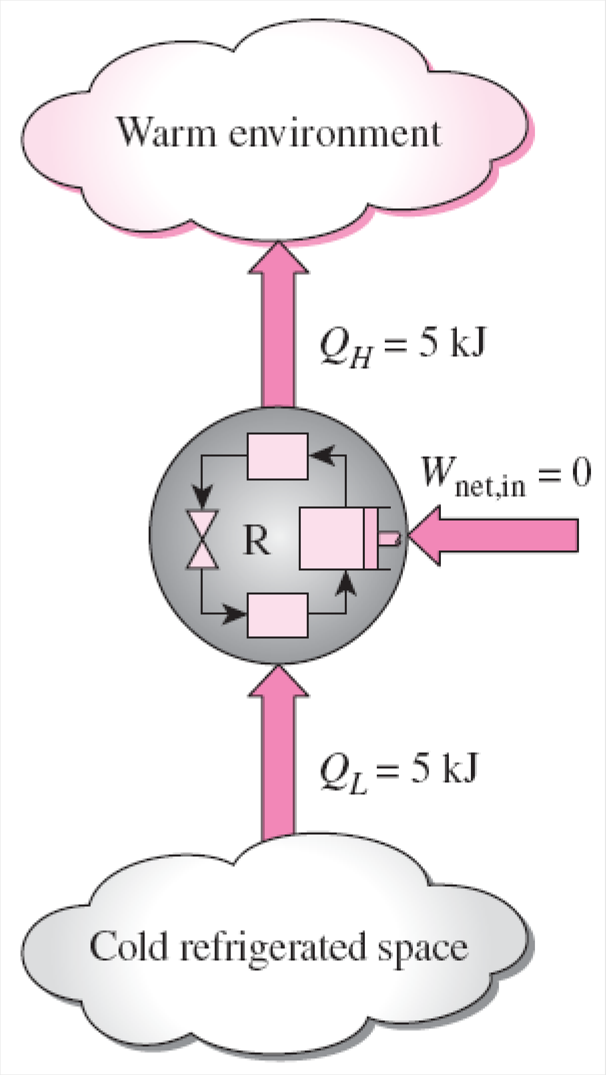
The Second Law of Thermodynamics: Clasius Statement

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.

It states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor.

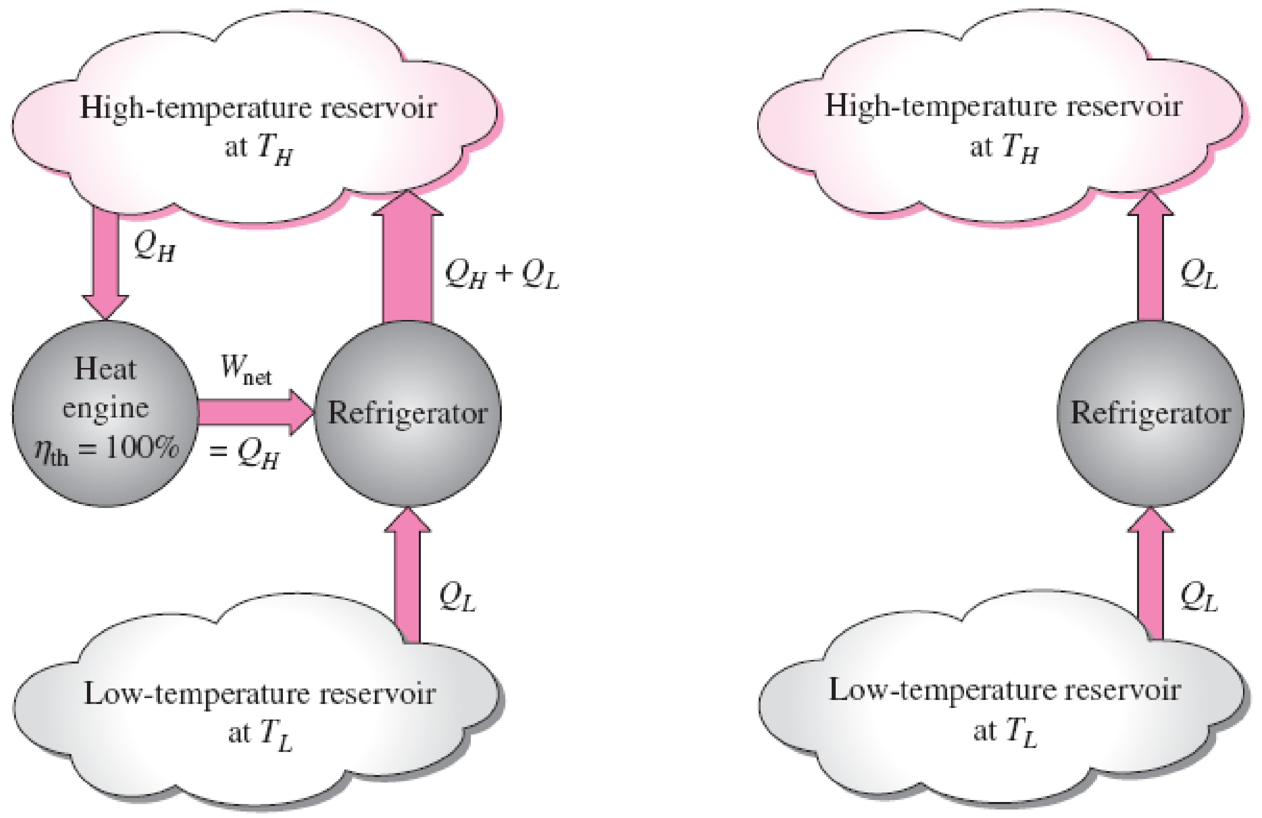
This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one.

To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity.



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

Equivalence of the Two Statements



(*a*) A refrigerator that is powered by a 100 percent efficient heat engine

(*b*) The equivalent refrigerator

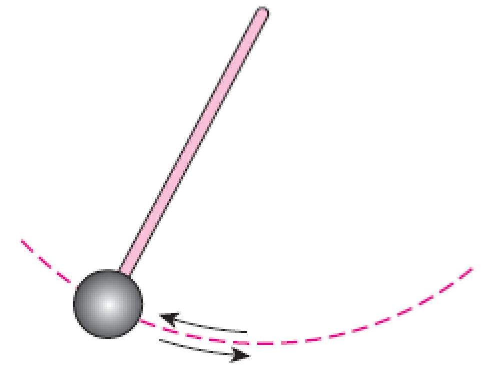
Proof that the violation of the Kelvin–Planck statement leads to the violation of the Clausius statement.

The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics.

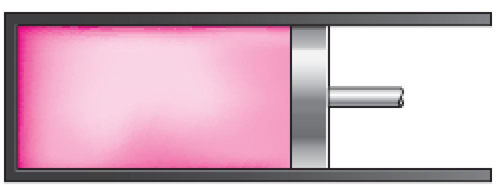
Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa.

REVERSIBLE AND IRREVERSIBLE PROCESSES

Reversible process: *A process that can be reversed without leaving any trace on the surroundings.*
Irreversible process: A process that is not reversible.



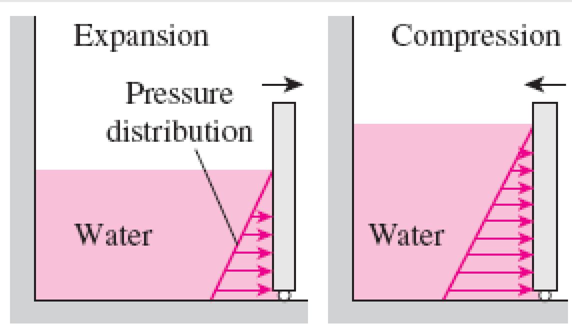
(*a*) Frictionless pendulum



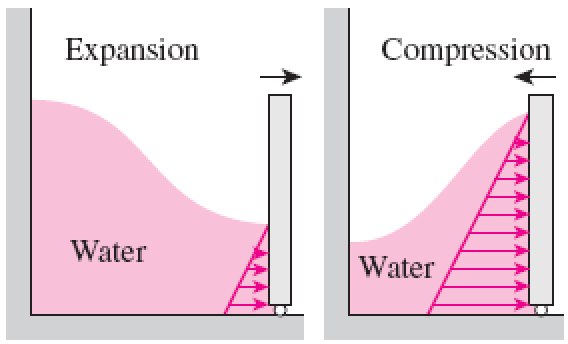
(*b*) Quasi-equilibrium expansion and compression of a gas

Two familiar reversible processes.

- All the processes occurring in nature are irreversible.
- ***Why are we interested* in reversible processes?**
- **(1)** they are easy to analyze and **(2)** they serve as idealized models (theoretical limits) to which actual processes can be compared.
- Some processes are more irreversible than others.
- We try to approximate reversible processes. **Why?**



(*a*) Slow (reversible) process

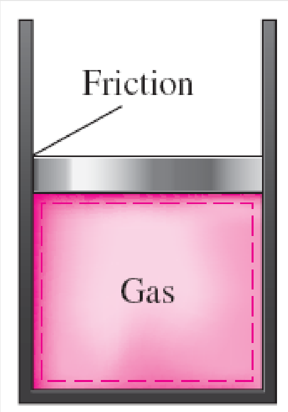


(*b*) Fast (irreversible) process

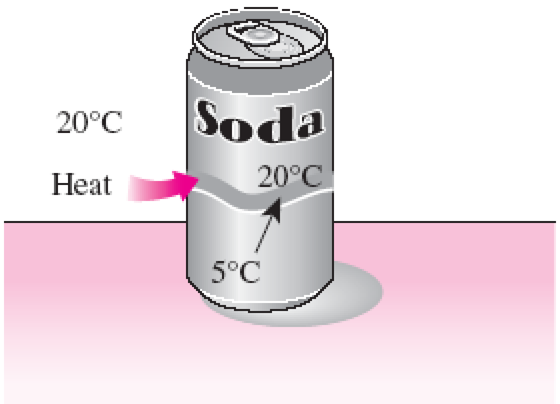
Reversible processes deliver the most and consume the least work.

Irreversibilities

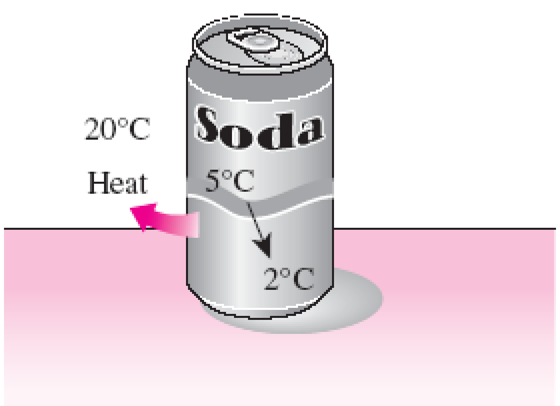
- The factors that cause a process to be irreversible are called **irreversibilities**.
- They include friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.
- The presence of any of these effects renders a process irreversible.



Friction renders a process irreversible.

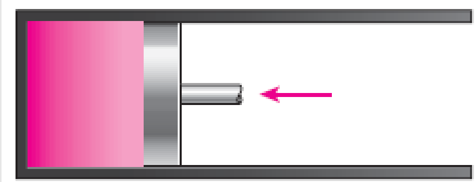


(*a*) An irreversible heat transfer process

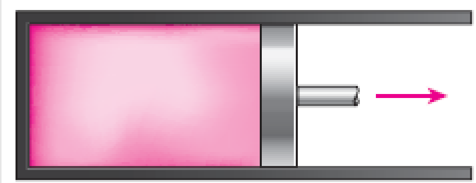


(*b*) An impossible heat transfer process

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



(*a*) Fast compression



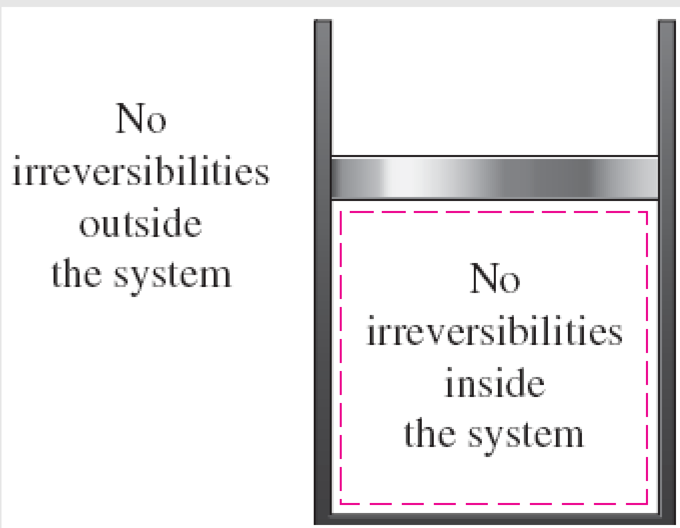
(*b*) Fast expansion

(*c*) Unrestrained expansion

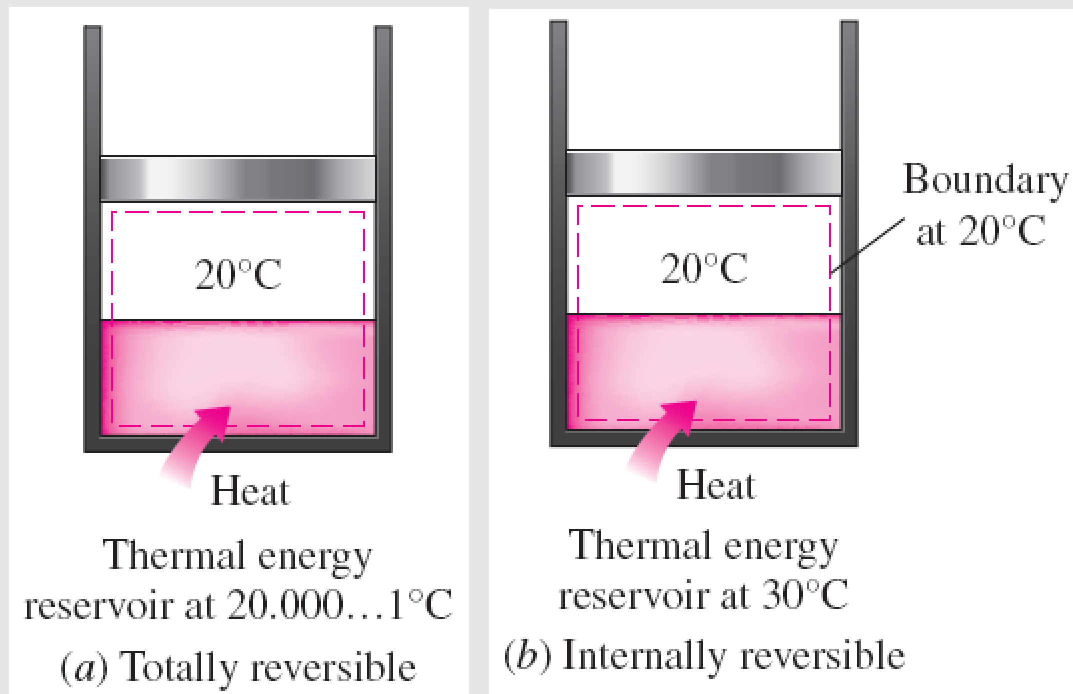
Irreversible compression and expansion processes.

Internally and Externally Reversible Processes

- **Internally reversible process:** If no irreversibilities occur within the boundaries of the system during the process.
- **Externally reversible:** If no irreversibilities occur outside the system boundaries.
- **Totally reversible process:** 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.



A reversible process involves no internal and external irreversibilities.



Totally and internally reversible heat transfer processes.

6.11 CARNOT CYCLE

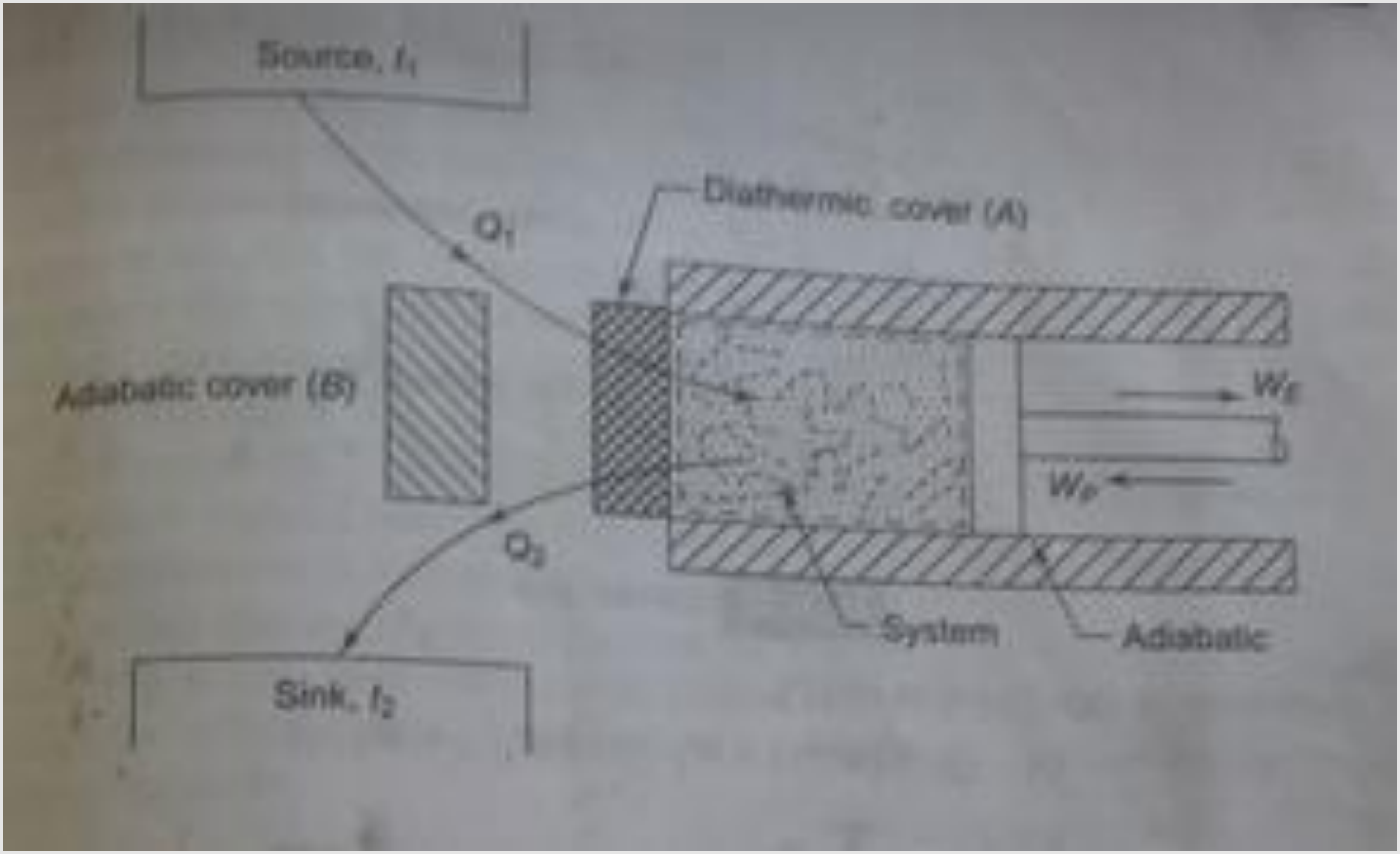
A reversible cycle is an ideal hypothetical cycle in which all the processes constituting the cycle are reversible. Carnot cycle is a reversible cycle. For a stationary system, as in a piston and cylinder machine, the cycle consists of the following four successive processes (Fig. 6.21):

1. *A reversible isothermal process* in which heat Q_1 enters the system at t_1 reversibly from a constant temperature source at t_1 when the cylinder cover is in contact with the diathermic cover A. The internal energy of the system increases.

From first law,

$$Q_1 = U_2 - U_1 + W_{1-2} \tag{6.14}$$

(for an ideal gas only, $U_1 = U_2$)



Source, t_1
Diathermic cover (A)
Q_1
Adiabatic cover (B)
W_E
W_P
Q_2
System
Adiabatic
Sink, t_2

2. *A reversible adiabatic process* in which the diathermic cover A is replaced by the adiabatic cover B, and work W_E is done by the system adiabatically and reversibly at the expense of its internal energy, and the temperature of the system decreases from t_1 to t_2.

Using the first law,

$$0 = U_3 - U_2 + W_{2-3} \tag{6.15}$$

3. *A reversible isothermal process* in which B is replaced by A and heat Q_2 leaves the system at t_2 to a constant temperature sink at t_2 reversibly, and the internal energy of the system further decreases.

From the first law,

$$-Q_2 = U_4 - U_3 - W_{3-4} \tag{6.16}$$

only for an ideal gas, $U_3 = U_4$

4. *A reversible adiabatic process* in which B again replaces A, and work W_p is done upon the system reversibly and adiabatically, and the internal energy of the system increases and the temperature rises from t_2 to t_1.

Applying the first law,

$$0 = U_1 - U_4 - W_{4-1} \tag{6.17}$$

Two reversible isotherms and two reversible adiabatics constitute a Carnot cycle, which is represented in p-v coordinates in Fig. 6.22.

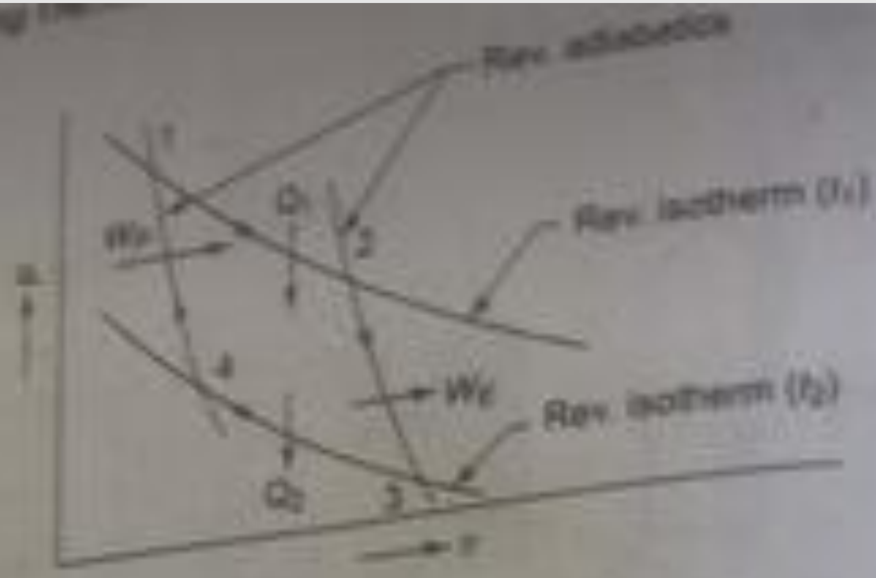


Fig. 6.22 Carnot cycle

Summing up Eqs. (6.14) to (6.17),

$$Q_1 - Q_2 = (W_{1-2} + W_{2-3}) - (W_{3-4} + W_{4-1})$$

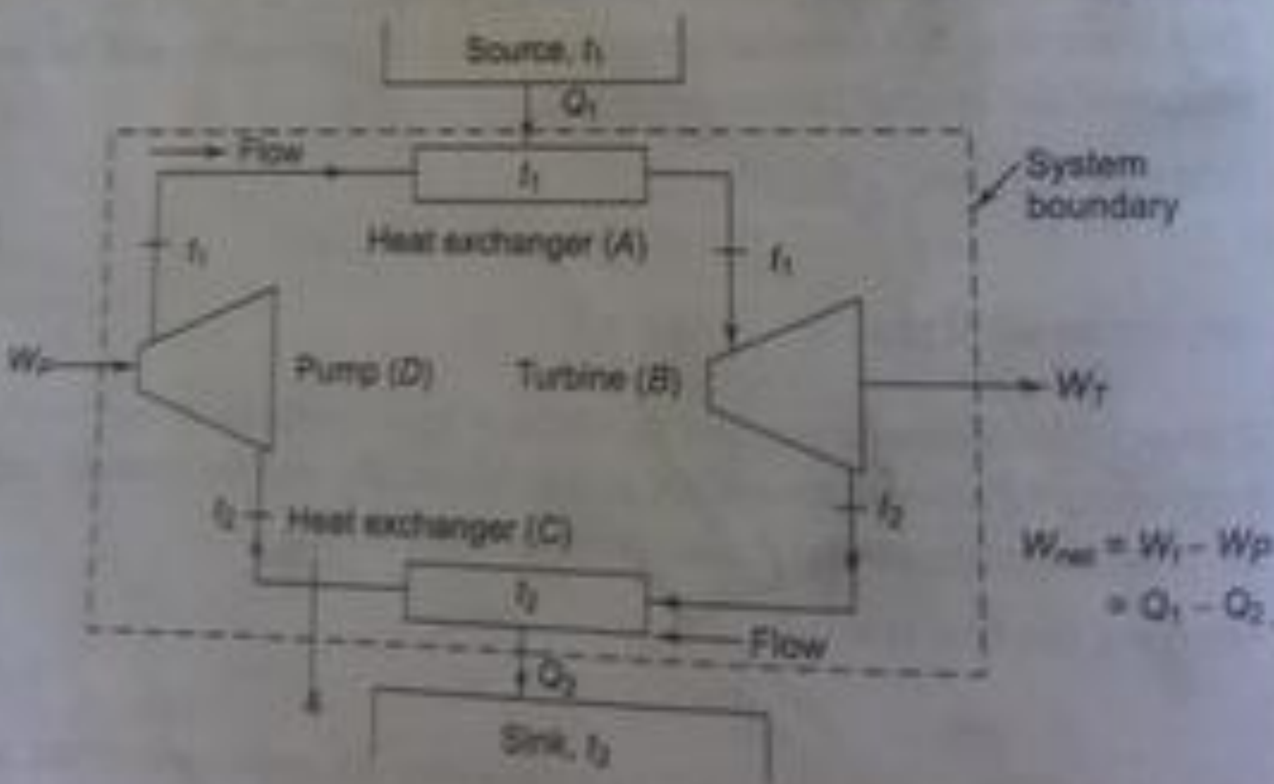
or

$$\sum_{\text{cycle}} Q_{\text{net}} = \sum_{\text{cycle}} W_{\text{net}}$$

...ine operating on the Carnot cycle is called a Carnot heat engine

A cyclic heat engine operating on the Carnot cycle is called a Carnot heat engine.

For a steady flow system, the Carnot cycle is represented as shown in Fig. 6.23. Here heat Q_1 is transferred to the system reversibly and isothermally at t_1 in the heat exchanger A, work W_T is done by the system reversibly and adiabatically in the turbine (B), then heat Q_2 is transferred from the system reversibly and isothermally at t_2 in the heat exchanger (C), and then work W_p is done upon the system reversibly and adiabatically by the pump (D). To satisfy the conditions for the Carnot cycle, there must not be any friction or heat transfer in the pipelines through which the working fluid flows.



6.12 REVERSED HEAT ENGINE

Since all the processes of the Carnot cycle are reversible, it is possible to imagine that the processes are individually reversed and carried out in reverse order. When a reversible process is reversed, all the energy transfers associated with the process are reversed in direction, but remain the same in magnitude. The reversed Carnot cycle for a steady flow system is shown in Fig. 6.24. The reversible heat engine and the reversed Carnot heat engine are represented in block diagrams in Fig. 6.25. If E is a reversible heat engine (Fig. 6.25a), and if it is reversed (Fig. 6.25b), the quantities Q_1, Q_2 and W remain the same in magnitude, and only their directions are reversed. The reversed heat engine Ǝ takes heat from a low temperature body, dis charges heat to a high temperature body, and receives an inward flow of network.

The names *heat pump* and *refrigerator* are applied to the reversed heat engine, which have already been discussed in Section 6.6, where the working fluid flows through the compressor (B), condenser (A), expander (D), and evaporator (C) to complete the cycle.

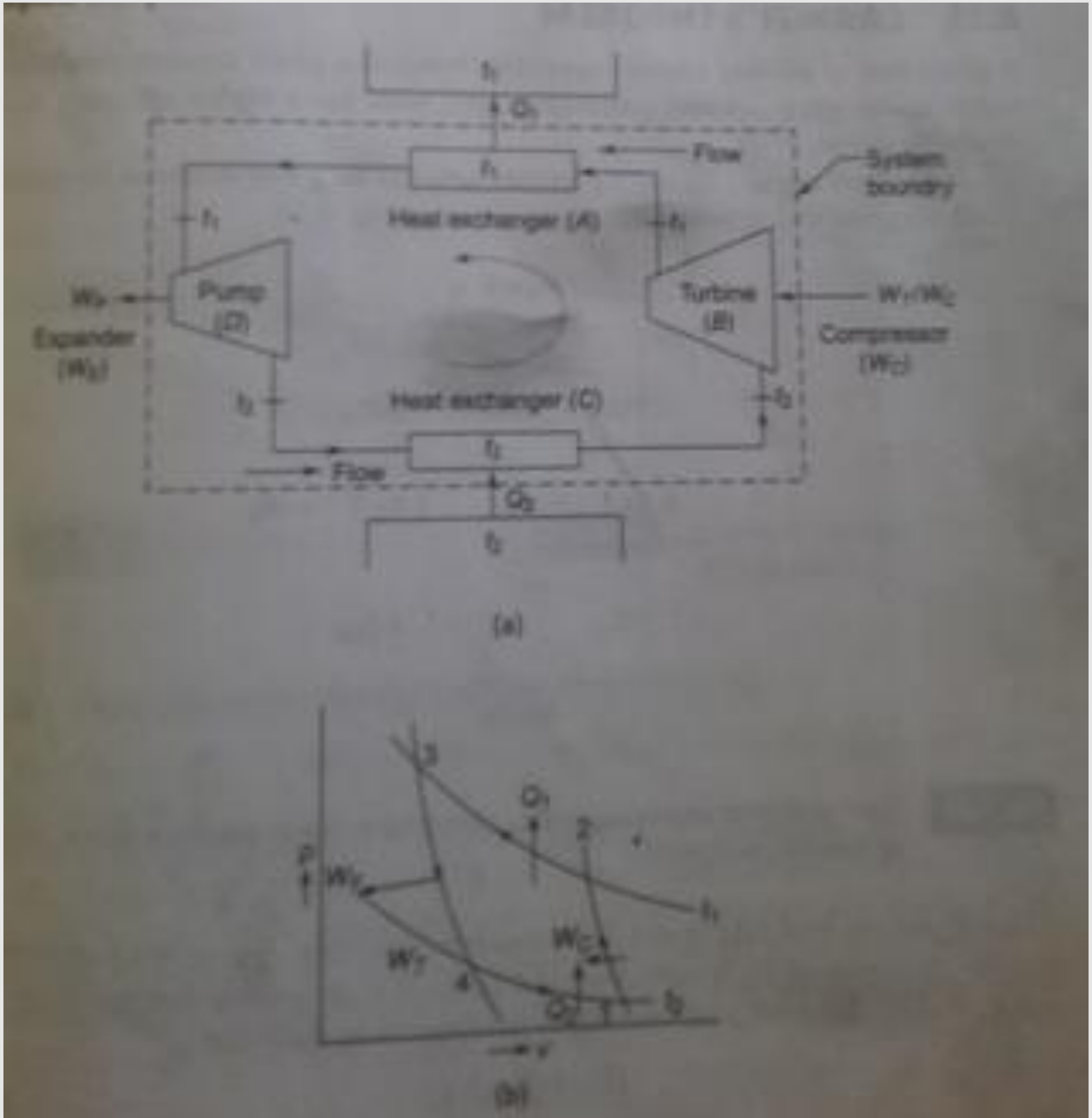


Fig. 6.28 Reversed Carnot heat engine—steady flow process

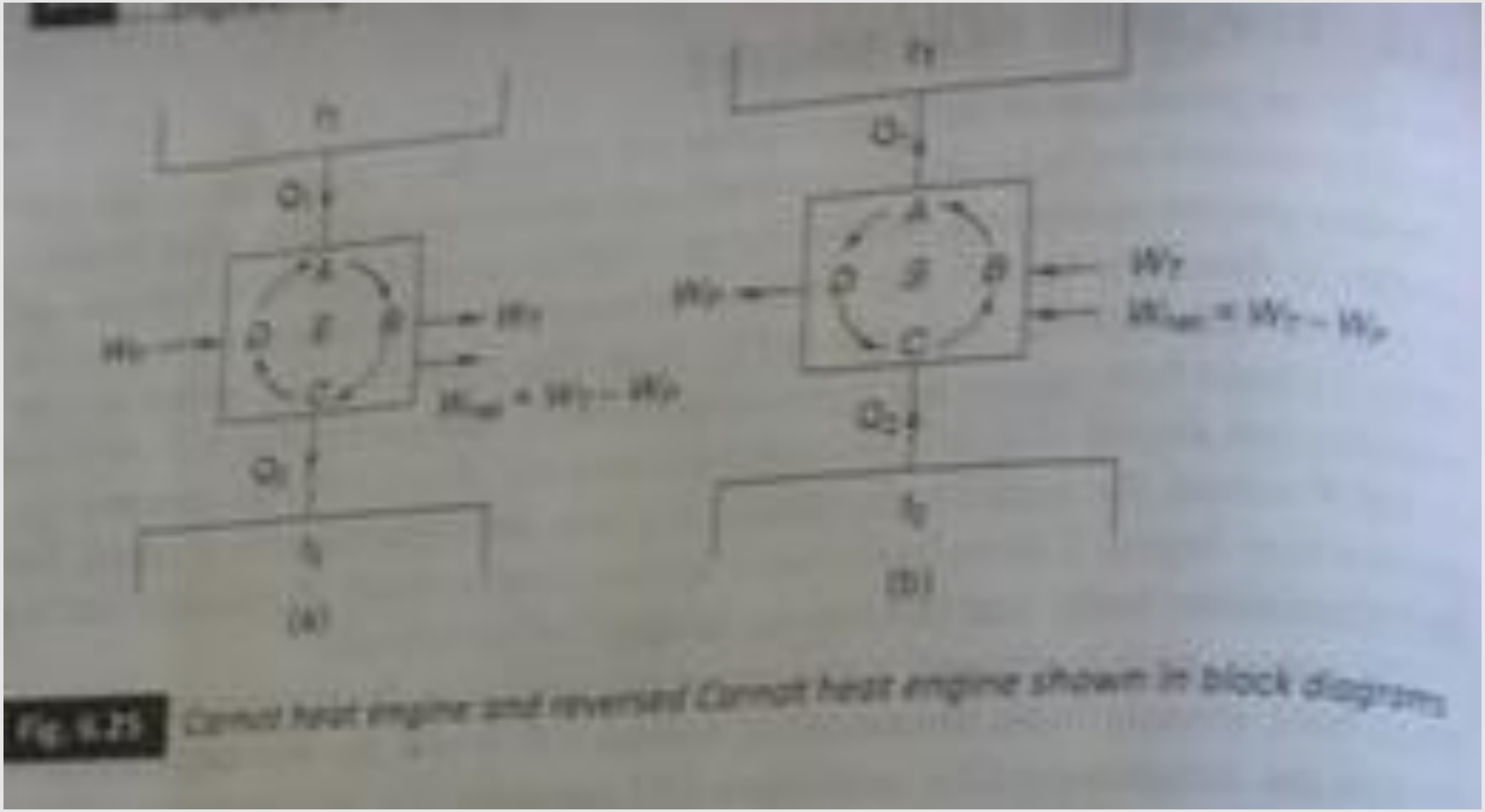


Fig. 9.25 Carnot heat engine and reversed Carnot heat engine shown in block diagrams

6.13 CARNOT'S THEOREM

It states that of all heat engines operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine.

Let two heat engines E_A and E_B operate between the given source at temperature t_1 and the given sink at temperature t_2 as shown in Fig. 6.26.

6.26 Two cyclic heat engines E_A and E_B operating between the same source and sink, of which E_B is reversible of which E_B is reversible ... operating between the same source and sink.

Let E_A be any heat engine and E_B be *any reversible* heat engine. We have to prove that the efficiency of E_B is more than that of E_A. Let us assume that this is not true and $\eta_A > \eta_B$. Let the rates of working of the engines be such that

$$Q_{1A} = Q_{1B} = Q_1$$

Since

$$\eta_A > \eta_B$$

$$\frac{W_A}{Q_{1A}} > \frac{W_B}{Q_{1B}}$$

$$W_A > W_B$$

Now, let E_B be reversed. Since E_B is a reversible heat engine, the magnitudes of heat and work transfer quantities will remain the same, but their directions will be reversed, as shown in Fig. 6.27. Since $W_A > W_B$, some part of W_A (equal to W_B) may be fed to drive the reversed heat engine $\exists_B$.

Since $Q_{1A} = Q_{1B} = Q_1$, the heat discharged by $\exists_B$ may be supplied to E_A. The source may, therefore, be eliminated (Fig. 6.28). The net result is that E_A and $\exists_B$ together constitute a heat engine which, operating in a cycle, produces net work $W_A - W_B$, while exchanging heat with a single reservoir at t_2. This violates the Kelvin-Planck statement of the second law. Hence the assumption that $\eta_A > \eta_B$ is wrong.

Therefore, $\eta_B \geq \eta_A$

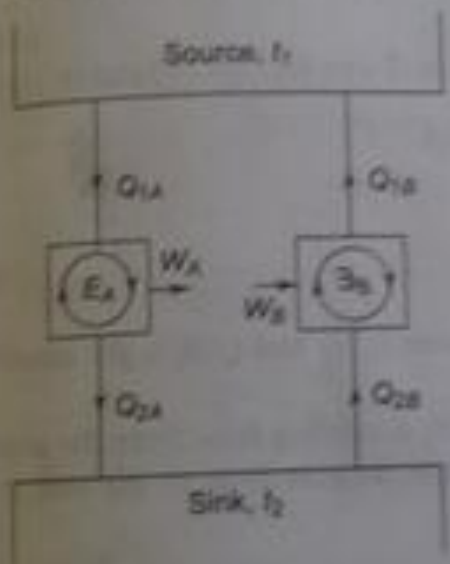


Fig. 6.27 E_B is reversed

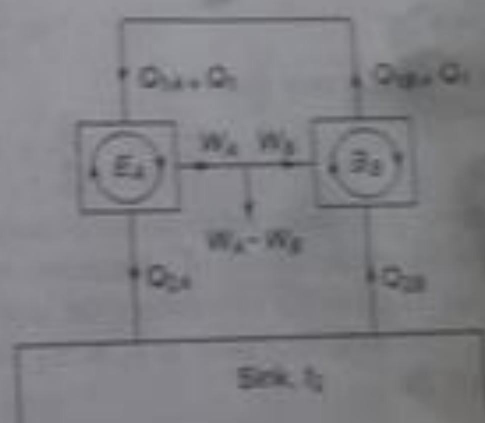


Fig. 6.28 E_A and $\exists_B$ together violate the K-P statement

6.14 COROLLARY OF CARNOT'S THEOREM

The efficiency of all reversible heat engines operating between the same temperat
levels is the same.

Let both the heat engines E_A and E_B (Fig. 6.26) be reversible. Let us ass
$\eta_A > \eta_B$. Similar to the procedure outlined in the preceding article, if E_B is rev
to run, say, as a heat pump using some part of the work output (W_A) of engine E
we that the combined system of heat pump E_B and engine E_A, becomes a PMM
η_A cannot be greater than η_B. Similarly, if we assume $\eta_B > \eta_A$ and reverse the
E_A, we observe that η_B cannot be greater than η_A.

Therefore,

$$\eta_A = \eta_B$$

$$\frac{W_A}{Q_{1A}} > \frac{W_B}{Q_{1B}}$$

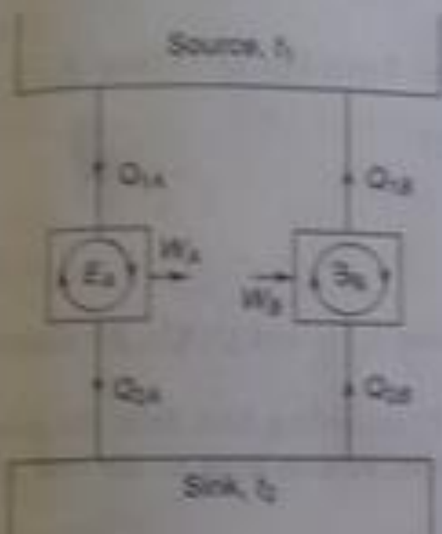
$$W_A > W_B$$

Now, let E_B be reversed. Since E_B is a reversible heat engine, the magnitudes of heat and work transfer quantities will remain the same, but their directions will be reversed, as shown in Fig. 6.27. Since $W_A > W_B$, some part of W_A (equal to W_B) may be fed to drive the reversed heat engine $\exists_B$.

Since $Q_{1A} = Q_{1B} = Q_1$, the heat discharged by $\exists_B$ may be supplied to E_A. The source may, therefore, be eliminated (Fig. 6.28). The net result is that E_A and $\exists_B$ together constitute a heat engine which, operating in a cycle, produces net work $W_A - W_B$, while exchanging heat with a single reservoir at t_2. This violates the Kelvin-Planck statement of the second law. Hence the assumption that $\eta_A > \eta_B$ is wrong.

Therefore,

$$\eta_B \geq \eta_A$$



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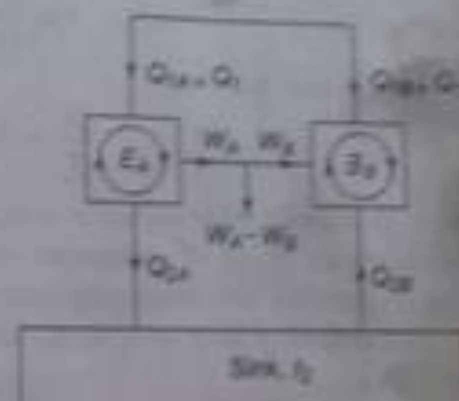

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Therefore,

$$\eta_A = \eta_B$$

heat reservoirs are ... nature or amount of the working substance ...

6.15 ABSOLUTE THERMODYNAMIC TEMPERATURE SCALE

The efficiency of any heat engine cycle receiving heat Q_1 and rejecting heat Q_2 is given by

$$\eta = \frac{W_{net}}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} \qquad (6.18)$$

By the second law, it is necessary to have a temperature difference $(t_1 - t_2)$ to obtain work for any cycle. We know that the efficiency of all heat engines operating between the same temperature levels is the same, and it is independent of the working substance. Therefore, for a reversible cycle (Carnot cycle), the efficiency will depend solely upon the temperatures t_1 and t_2, at which heat is transferred, or

$$\eta_{rev} = f(t_1, t_2) \qquad (6.19)$$

where f signifies some function of the temperatures. From Eqs. (6.18) and (6.19)

$$1 - \frac{Q_2}{Q_1} = f(t_1, t_2)$$

In terms of a new function F

$$\frac{Q_1}{Q_2} = F(t_1, t_2) \qquad (6.20)$$

If some functional relationship is assigned between t_1, t_2 and Q_1/Q_2, the equation becomes the definition of a temperature scale.

Let us consider two reversible heat engines, E_1 receiving heat from the source at t_1, and rejecting heat at t_2 to E_2 which, in turn, rejects heat to the sink at t_3 (Fig. 6.29a).

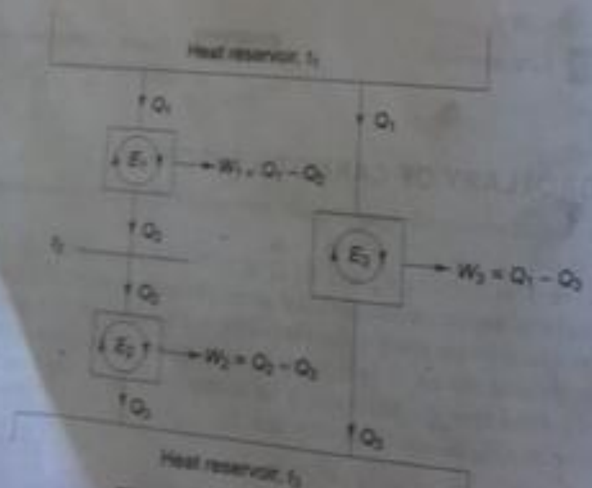

Fig. 6.29 (a) Three Carnot engines

The efficiency of any heat engine

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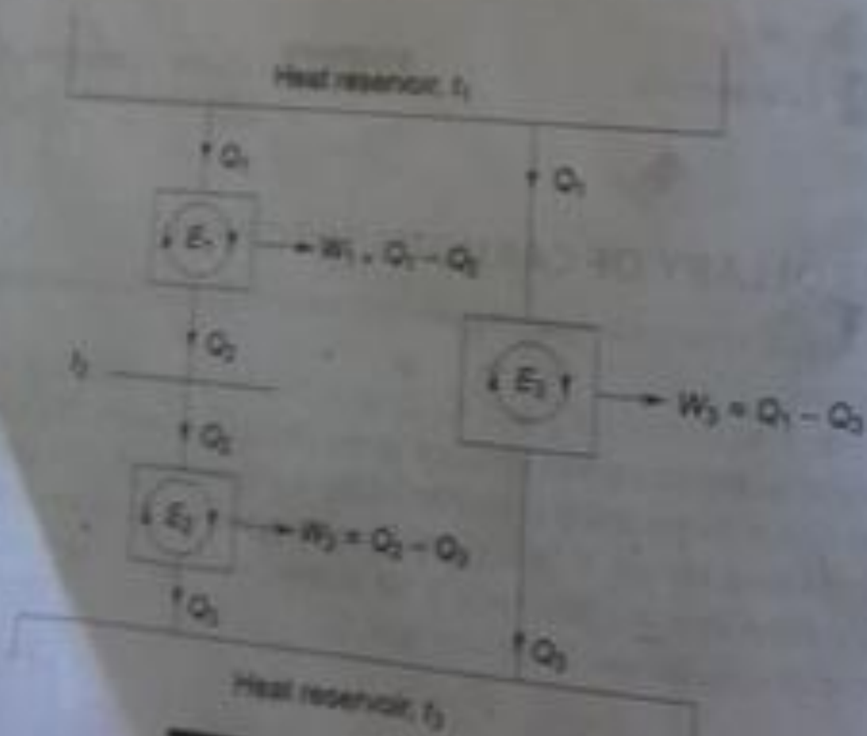


Fig. 6.29 (a) Three Carnot engines

Now $$\frac{Q_1}{Q_2}=F(t_1,t_2);\ \frac{Q_2}{Q_3}=F(t_2,t_3)$$

E_1 and E_2 together constitute another heat engine E_3 operating between t_1 and t_3.

∴ $$\frac{Q_1}{Q_3}=F(t_1,t_3)$$

Now $$\frac{Q_1}{Q_2}=\frac{Q_1/Q_3}{Q_2/Q_3}$$

or $$\frac{Q_1}{Q_2}=F(t_1,t_2)=\frac{F(t_1,t_3)}{F(t_2,t_3)} \tag{6.21}$$

The temperatures t_1, t_2 and t_3 are arbitrarily chosen. The ratio Q_1/Q_2 depends only on t_1 and t_2, and is independent of t_3. So t_3 will drop out from the ratio on the right in Eq. (6.21). After it has been cancelled, the numerator can be written as $\phi(t_1)$, and the denominator as $\phi(t_2)$, where ϕ is another unknown function. Thus,

$$\frac{Q_1}{Q_2}=F(t_1,t_2)=\frac{\phi(t_1)}{\phi(t_2)}$$

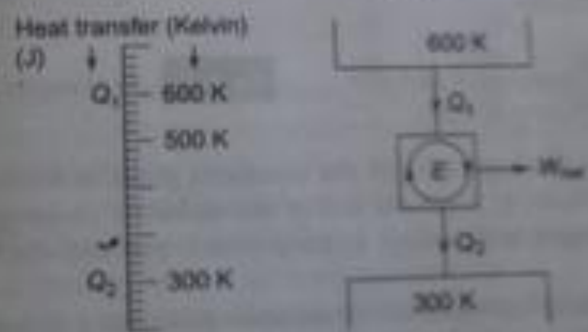


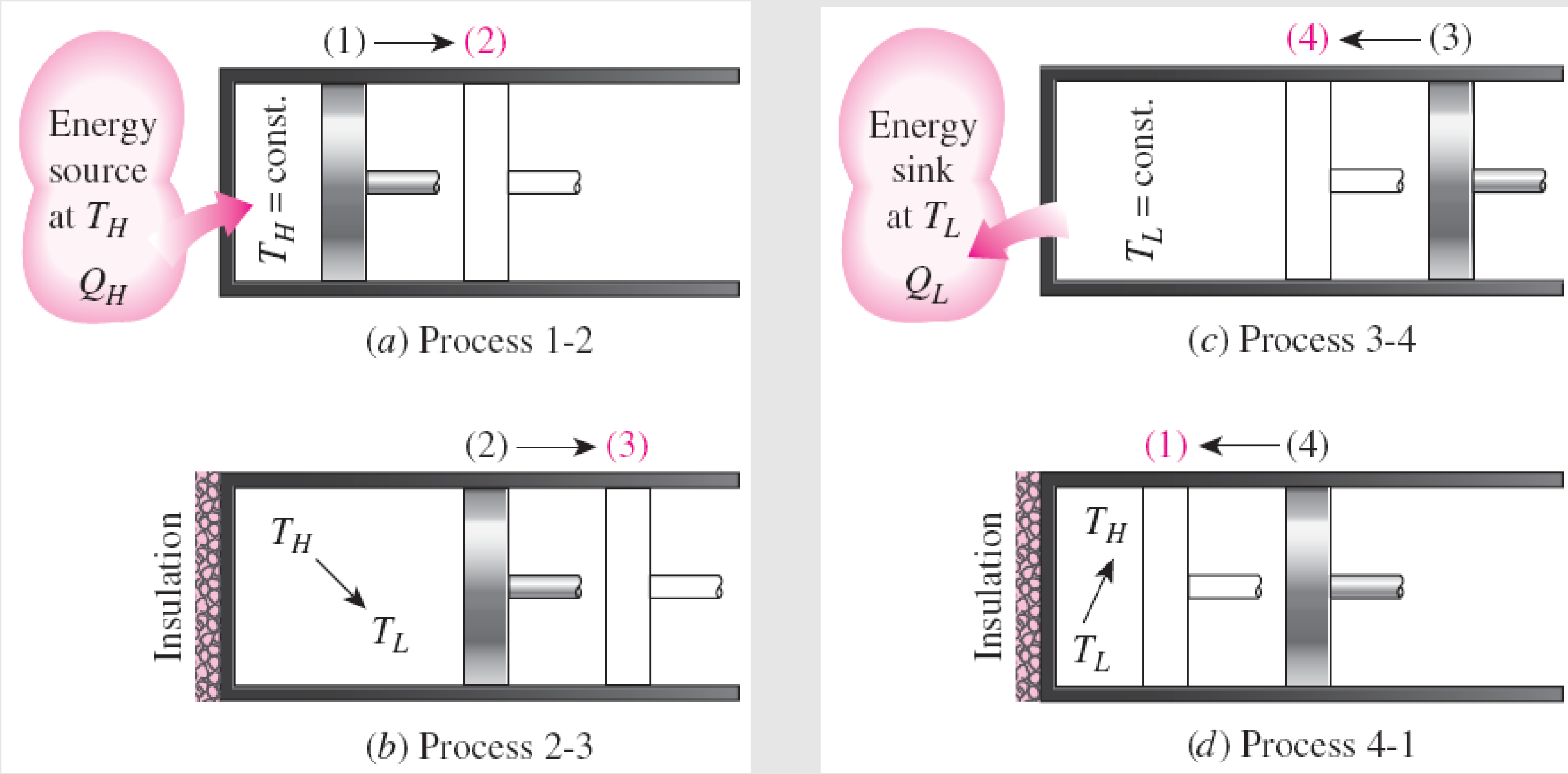
Fig. 6.29 (b)

Since $\phi(t)$ is an arbitrary function, the simplest possible way to define the absolute thermodynamic temperature T is to let $\phi(t)=T$, as proposed by Kelvin. Then, by definition

$$\frac{Q_1}{Q_2}=\frac{T_1}{T_2} \tag{6.22}$$

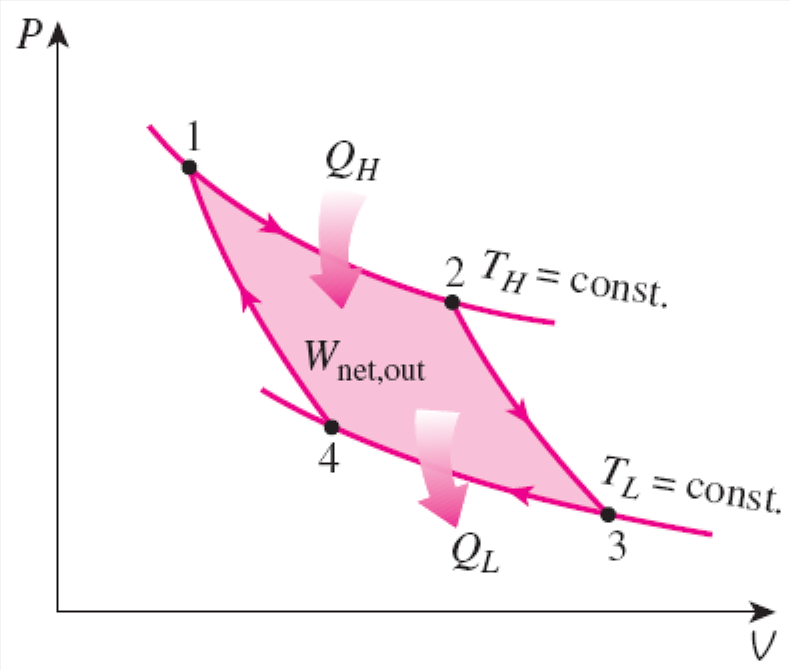
The absolute thermodynamic temperature scale is also known as the *Kelvin scale*. Two temperatures on the Kelvin scale bear the same relationship to each other as do

THE CARNOT CYCLE

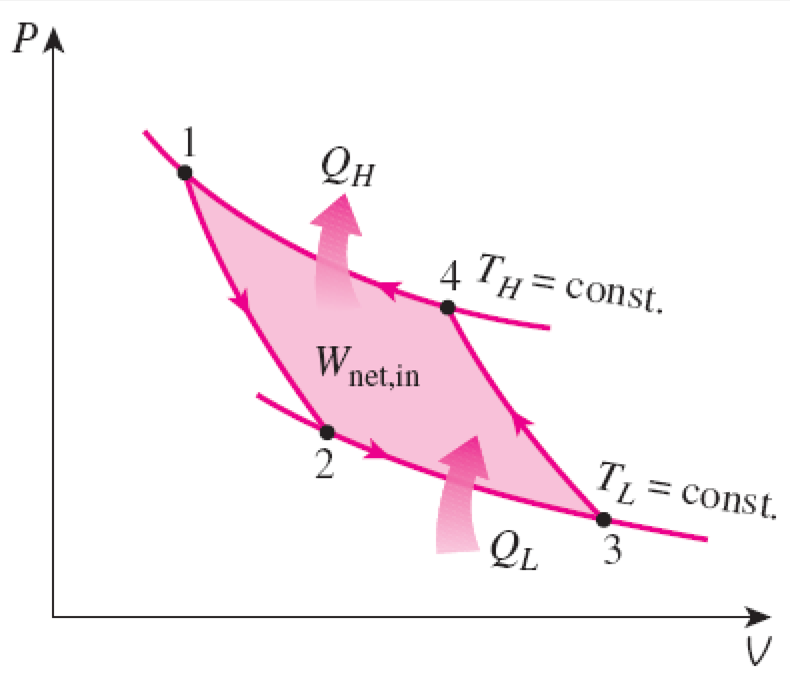


Execution of the Carnot cycle in a closed system.

Reversible Isothermal Expansion (process 1-2, T_H = constant)
Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H to T_L)
Reversible Isothermal Compression (process 3-4, T_L = constant)
Reversible Adiabatic Compression (process 4-1, temperature rises from T_L to T_H)



P-V diagram of the Carnot cycle.



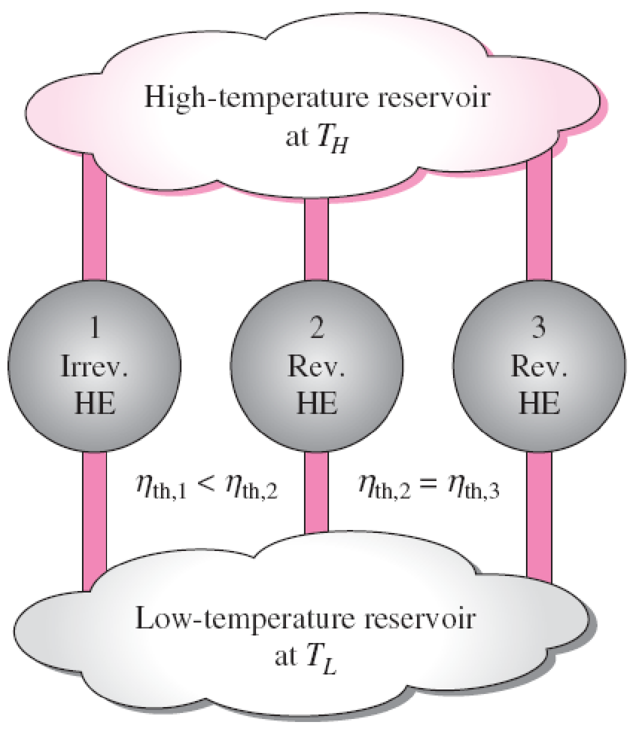
P-V diagram of the reversed Carnot cycle.

The Reversed Carnot Cycle

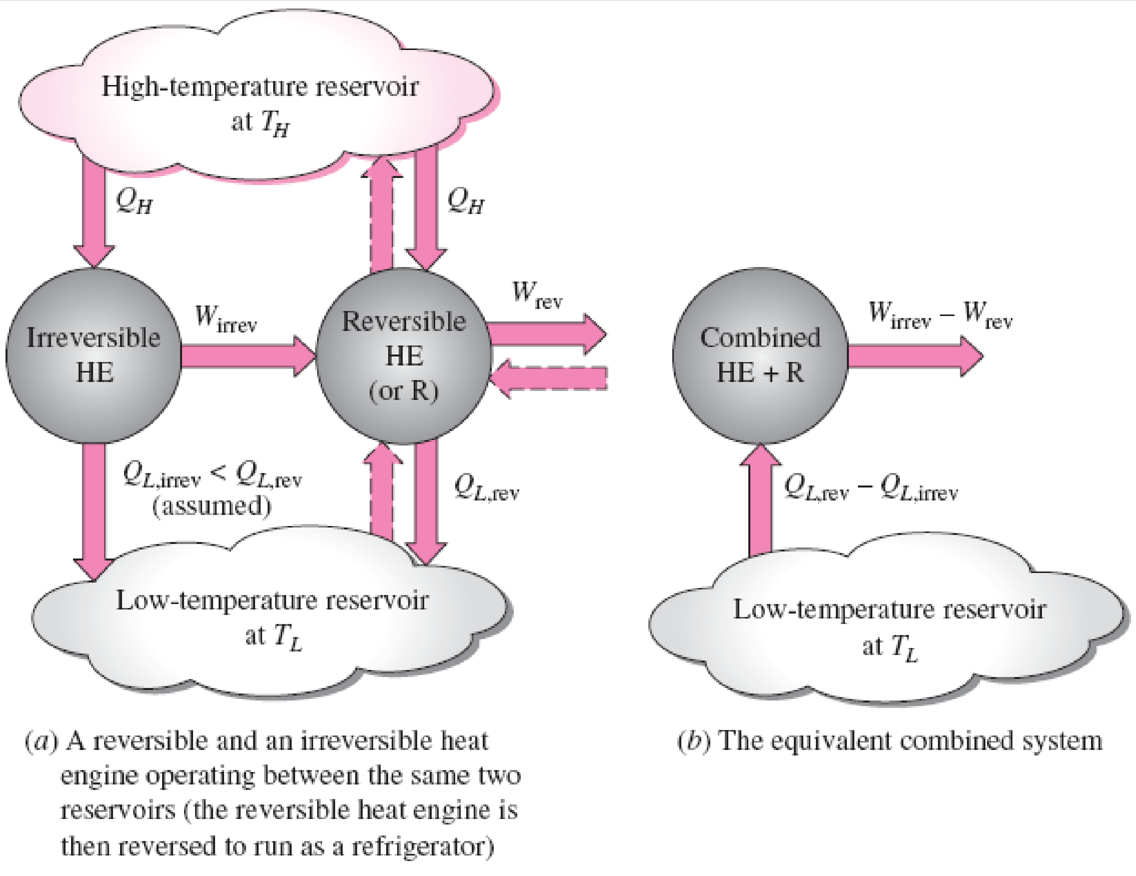
The Carnot heat-engine cycle is a totally reversible cycle.

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

THE CARNOT PRINCIPLES



The Carnot principles.



Proof of the first Carnot principle.

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.

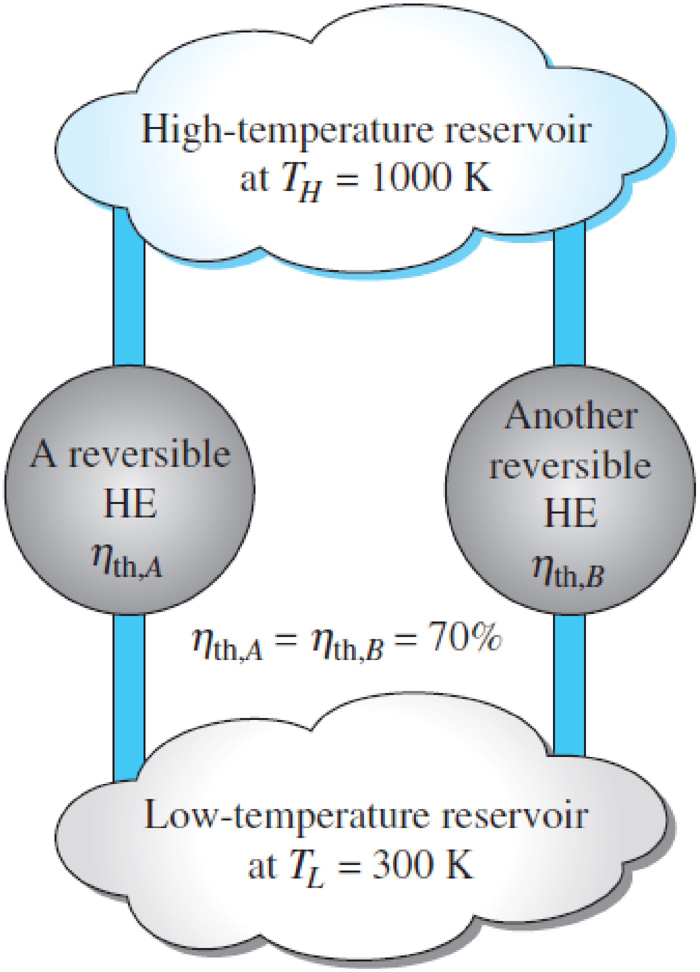


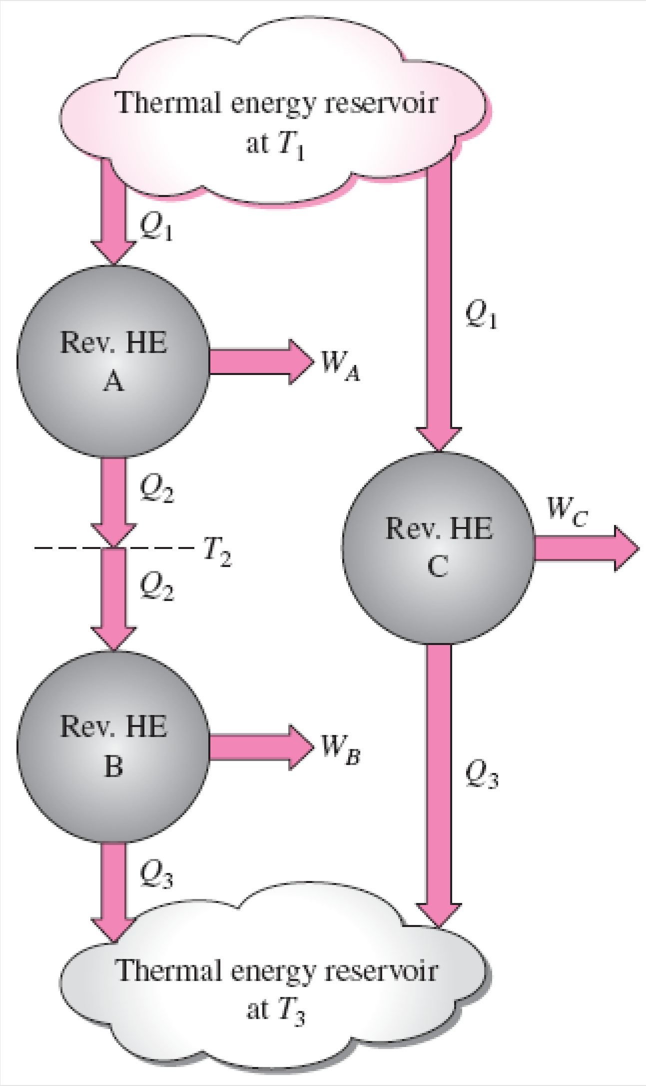
FIGURE 7–40

All reversible heat engines operating between the same two reservoirs have the same efficiency (the second Carnot principle).

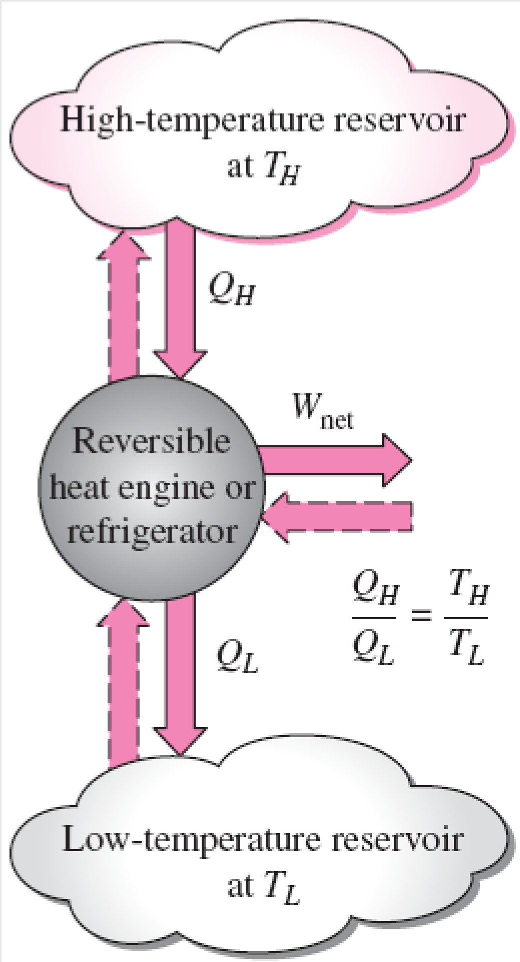
THE THERMODYNAMIC TEMPERATURE SCALE

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

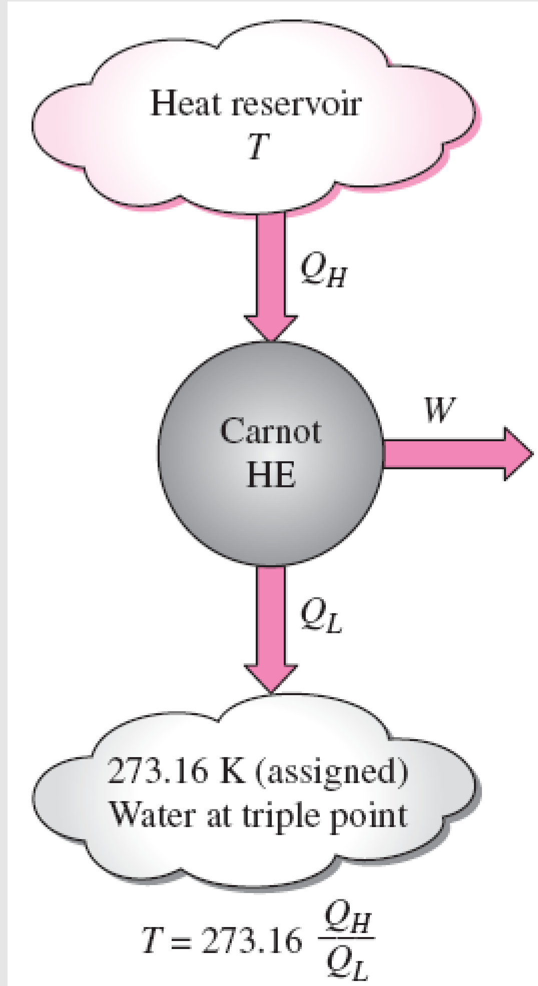
Such a temperature scale offers great conveniences in thermodynamic calculations.



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



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



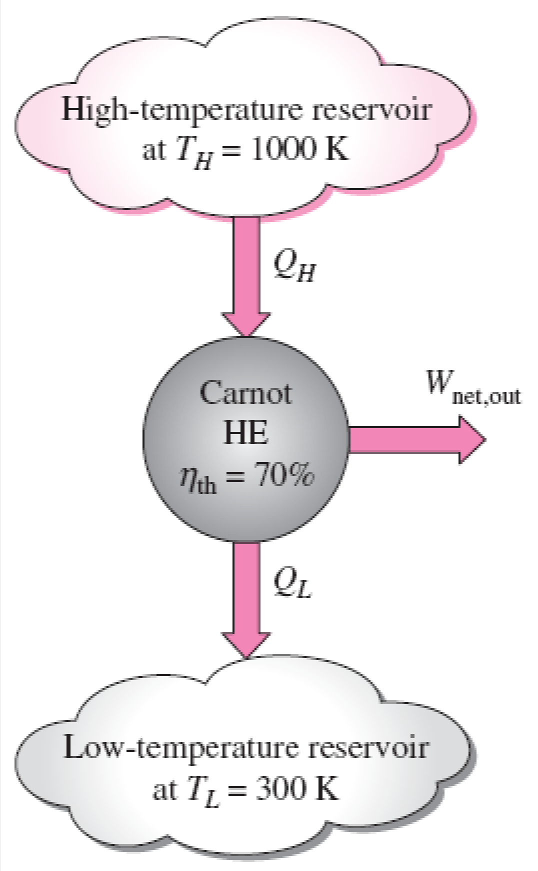
A conceptual experimental setup to determine thermodynamic temperatures on the Kelvin scale by measuring heat transfers Q_H and Q_L.

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

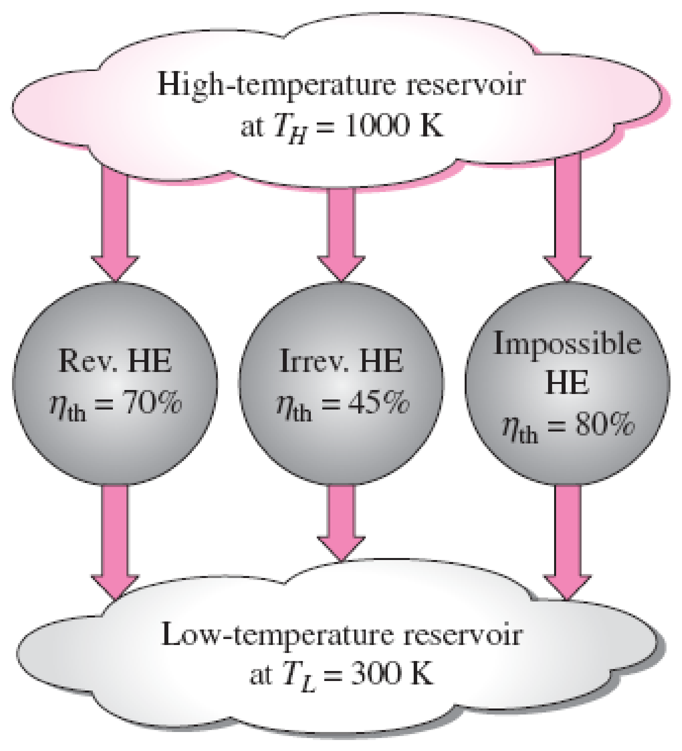
This temperature scale is called the **Kelvin scale**, and the temperatures on this scale are called **absolute temperatures**.

$$T(°C) = T(K) - 273.15$$

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.

Any heat engine

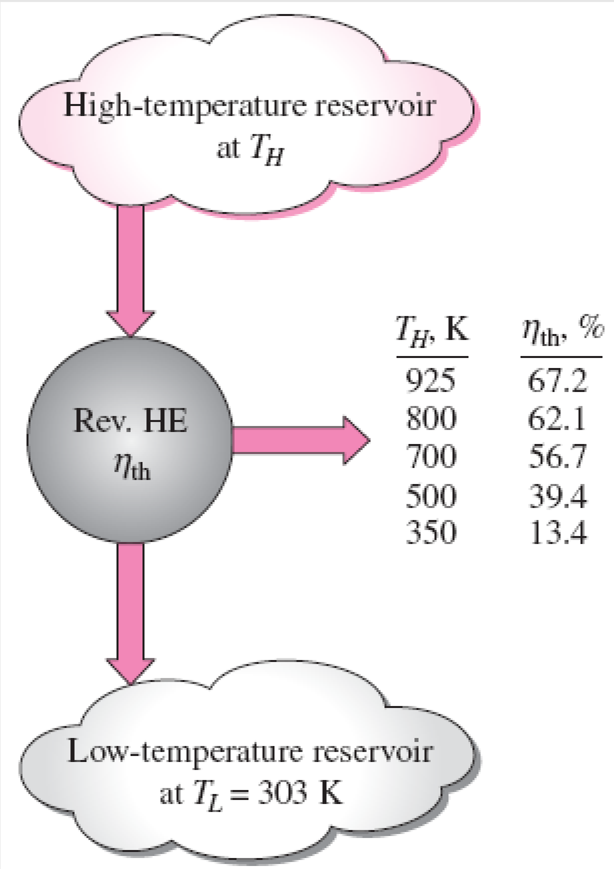
$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

Carnot heat engine

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

$$\eta_{th} \begin{cases} < \eta_{th,rev} & \text{irreversible heat engine} \\ = \eta_{th,rev} & \text{reversible heat engine} \\ > \eta_{th,rev} & \text{impossible heat engine} \end{cases}$$

The Quality of Energy

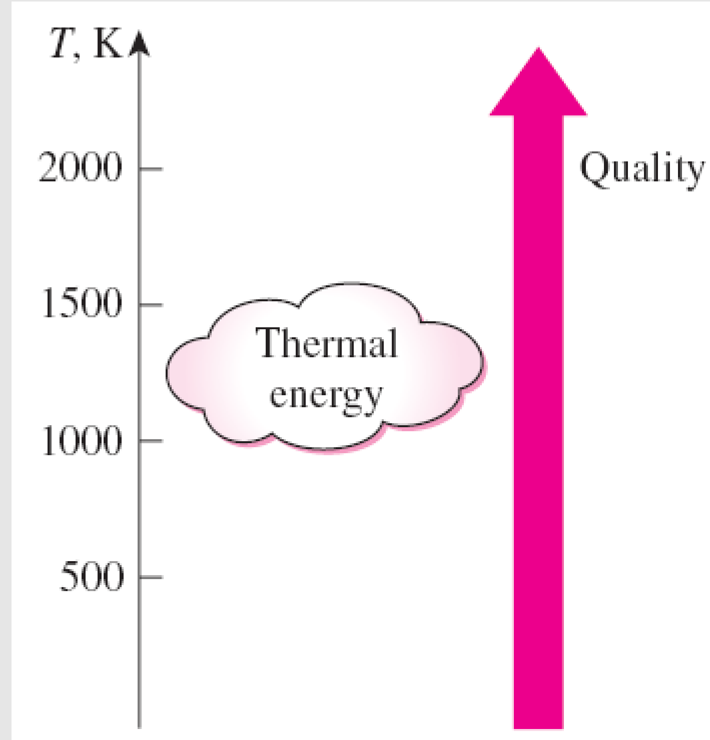


T_H, K	η_{th}, %
925	67.2
800	62.1
700	56.7
500	39.4
350	13.4

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

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

Can we use °C unit for temperature here?

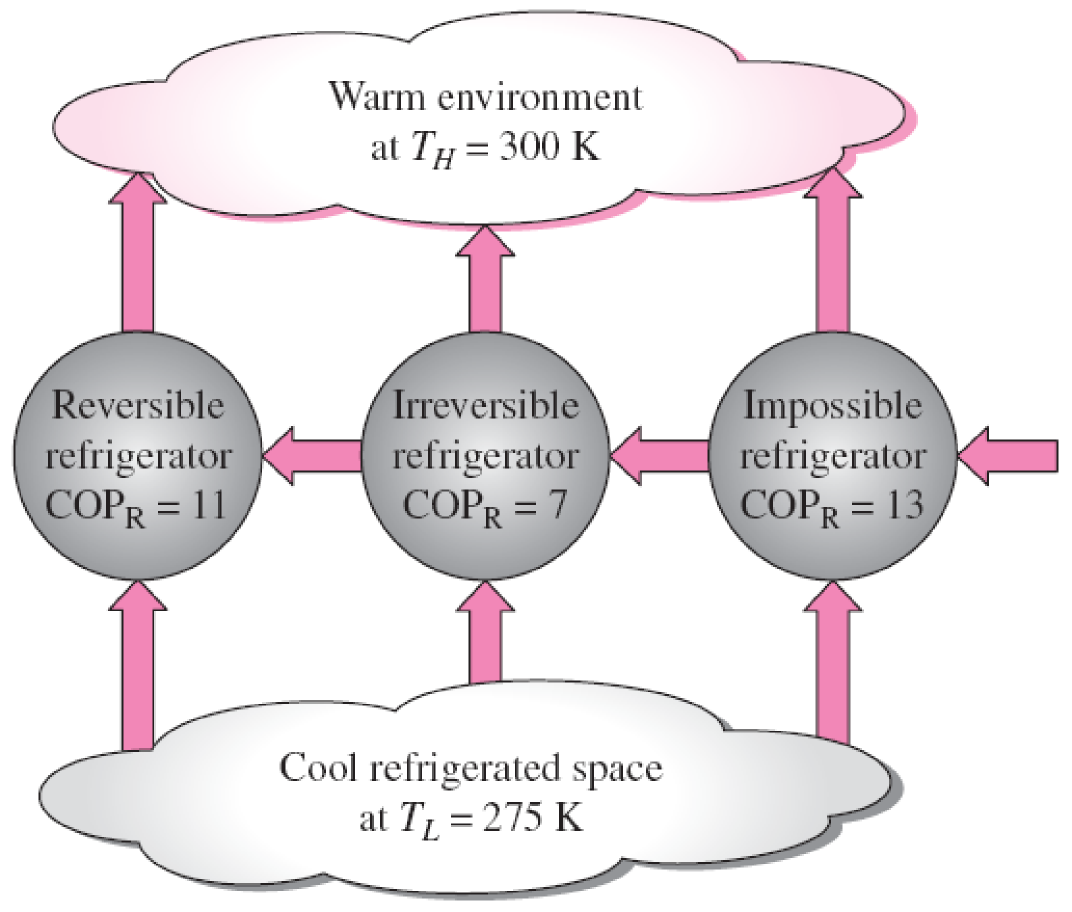


The higher the temperature of the thermal energy, the higher its quality.

How do you increase the thermal efficiency of a Carnot heat engine?

How about for actual heat engines?

7-10 THE CARNOT REFRIGERATOR AND HEAT PUMP



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

Any refrigerator or heat pump

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

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

Carnot refrigerator or heat pump

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

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

How do you increase the COP of a Carnot refrigerator or heat pump? How about for actual ones?

$$\mathrm{COP_R}\begin{cases} < \mathrm{COP_{R,rev}} & \text{irreversible refrigerator} \\ = \mathrm{COP_{R,rev}} & \text{reversible refrigerator} \\ > \mathrm{COP_{R,rev}} & \text{impossible refrigerator} \end{cases}$$

The COP of a reversible refrigerator or heat pump is the maximum theoretical value for the specified temperature limits.

Actual refrigerators or heat pumps may approach these values as their designs are improved, but they can never reach them.

The COPs of both the refrigerators and the heat pumps decrease as T_L decreases.

That is, it requires more work to absorb heat from lower-temperature media.