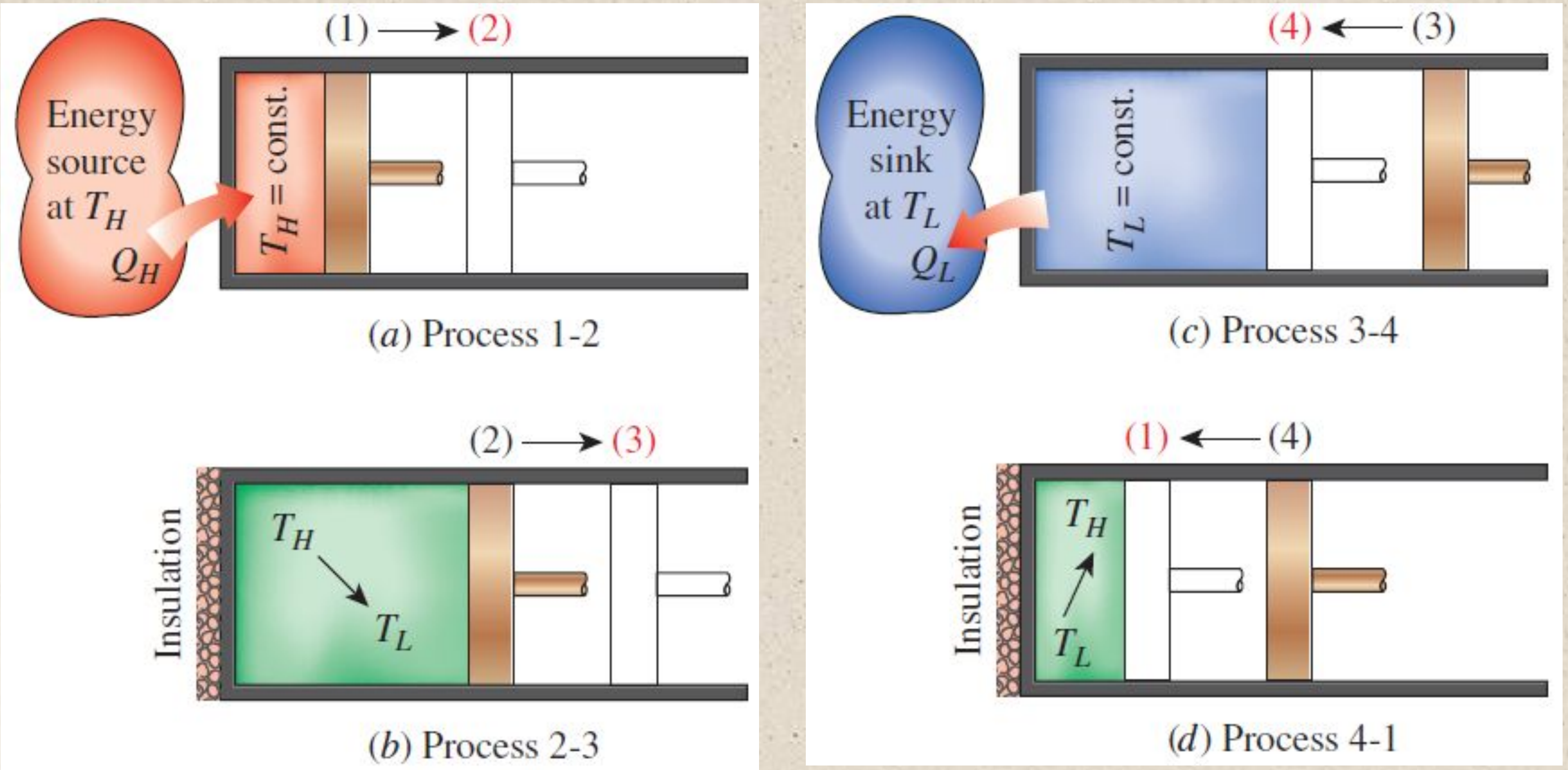
THE CARNOT CYCLE



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)

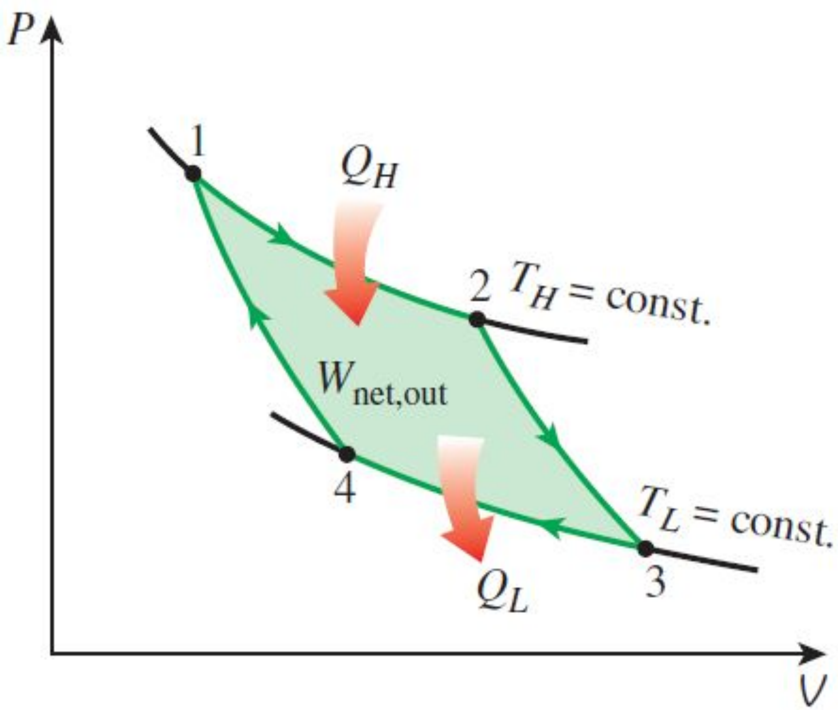


FIGURE 6–37

P-*V* diagram of the Carnot cycle.

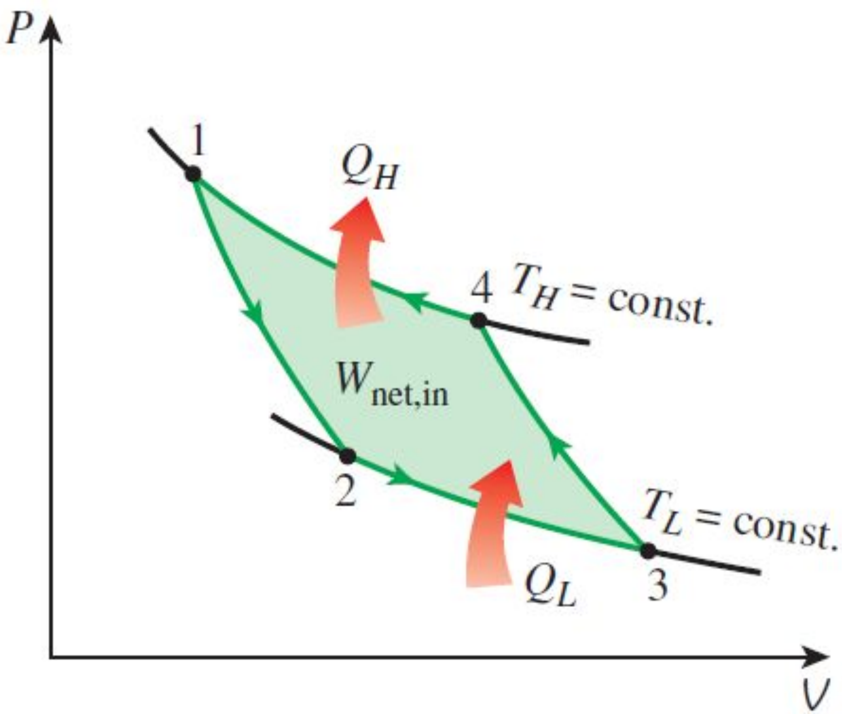


FIGURE 6–38

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.

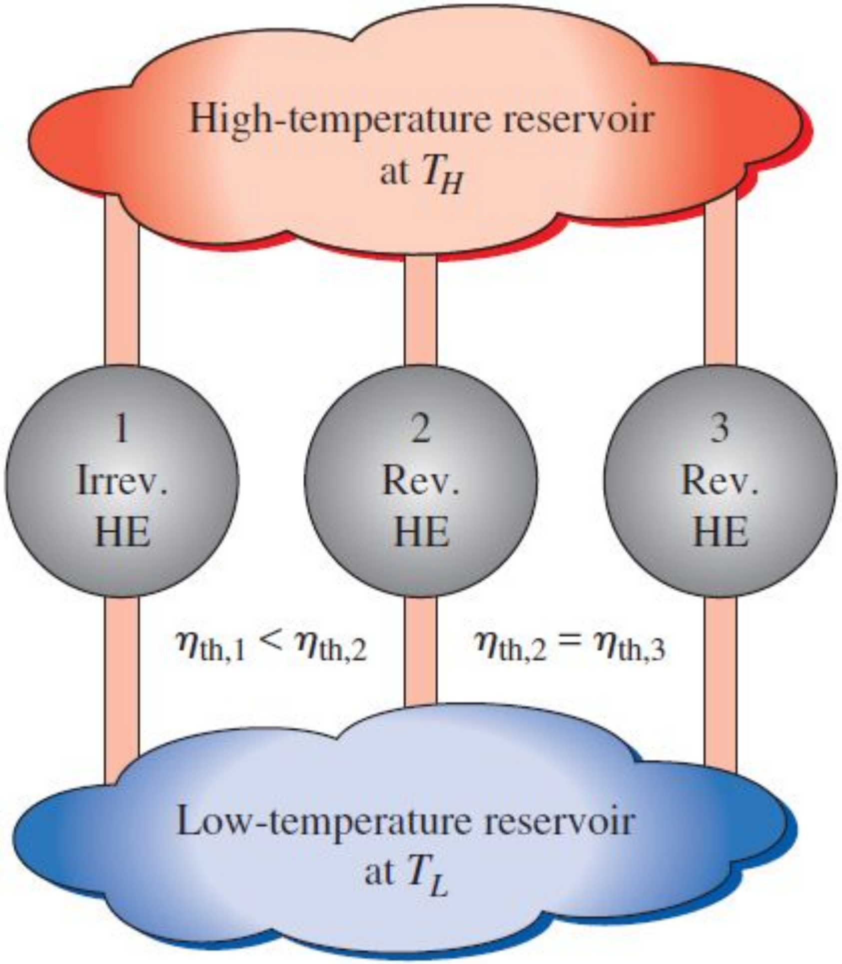
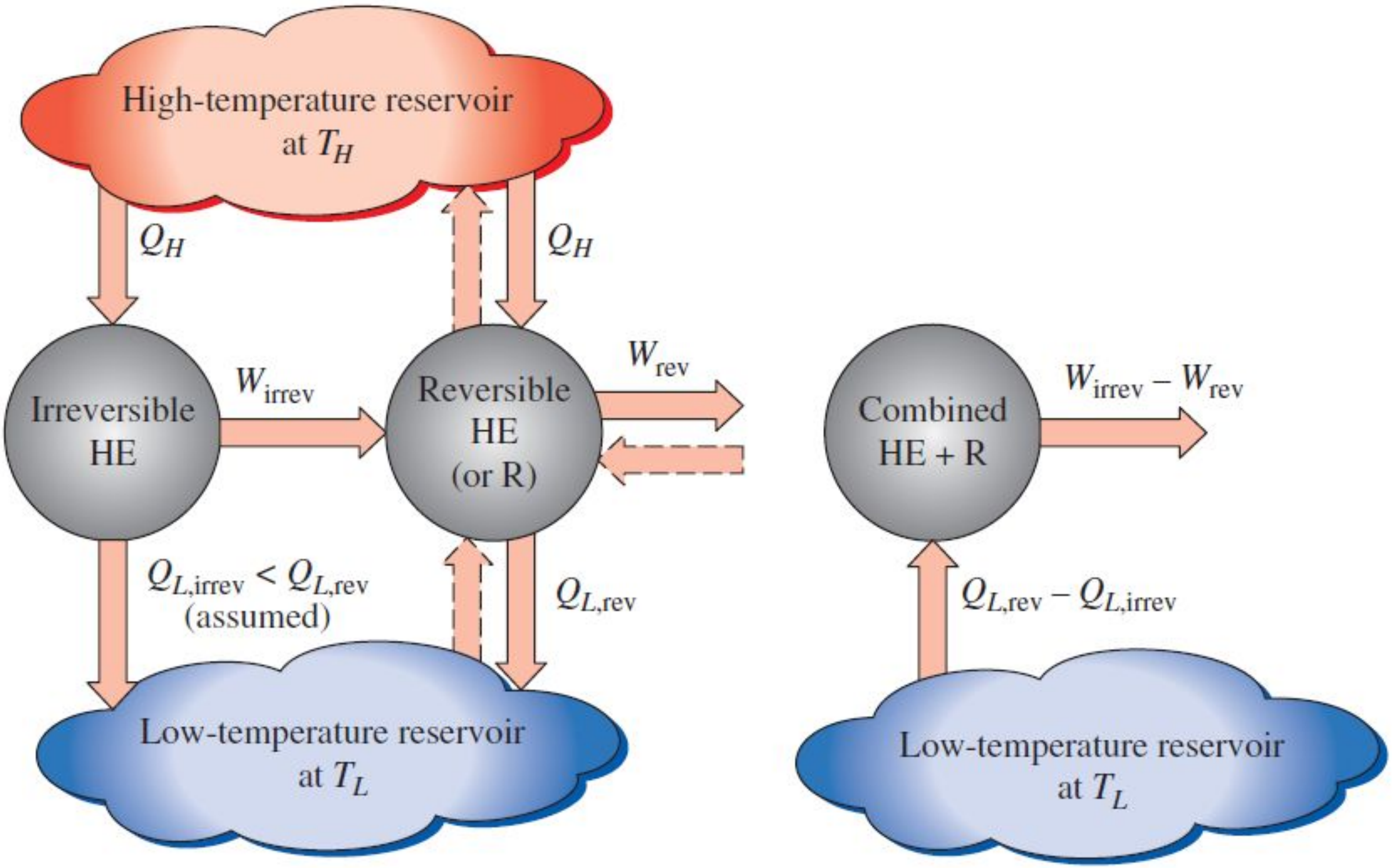


FIGURE 6–39
The Carnot principles.



(*a*) A reversible and an irreversible heat engine operating between the same two reservoirs (the reversible heat engine is then reversed to run as a refrigerator)

(*b*) The equivalent combined system

FIGURE 6–40
Proof of the first Carnot principle.

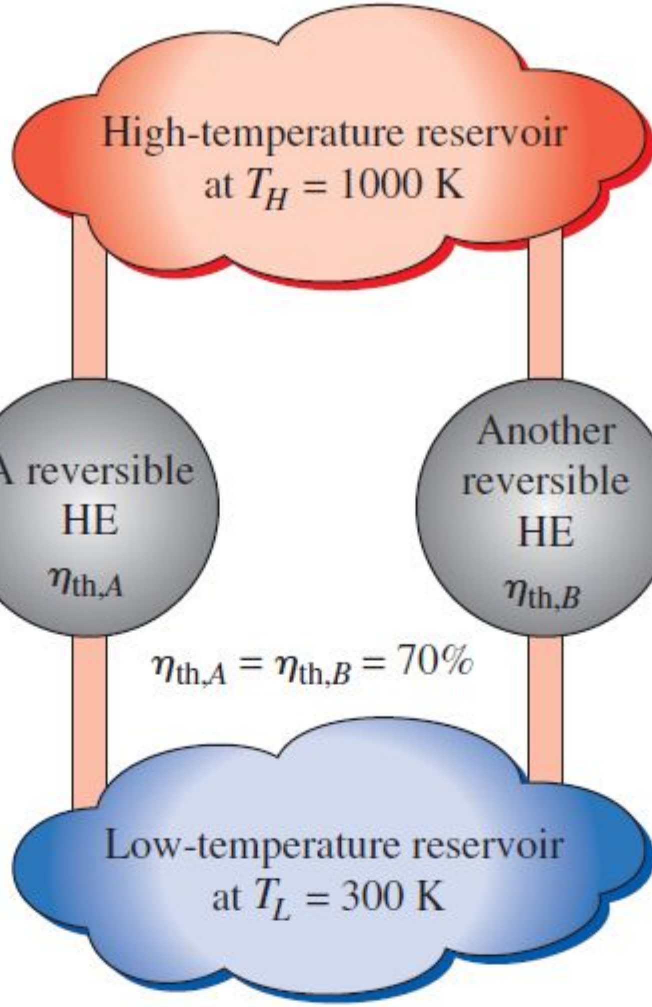


FIGURE 6–41

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.

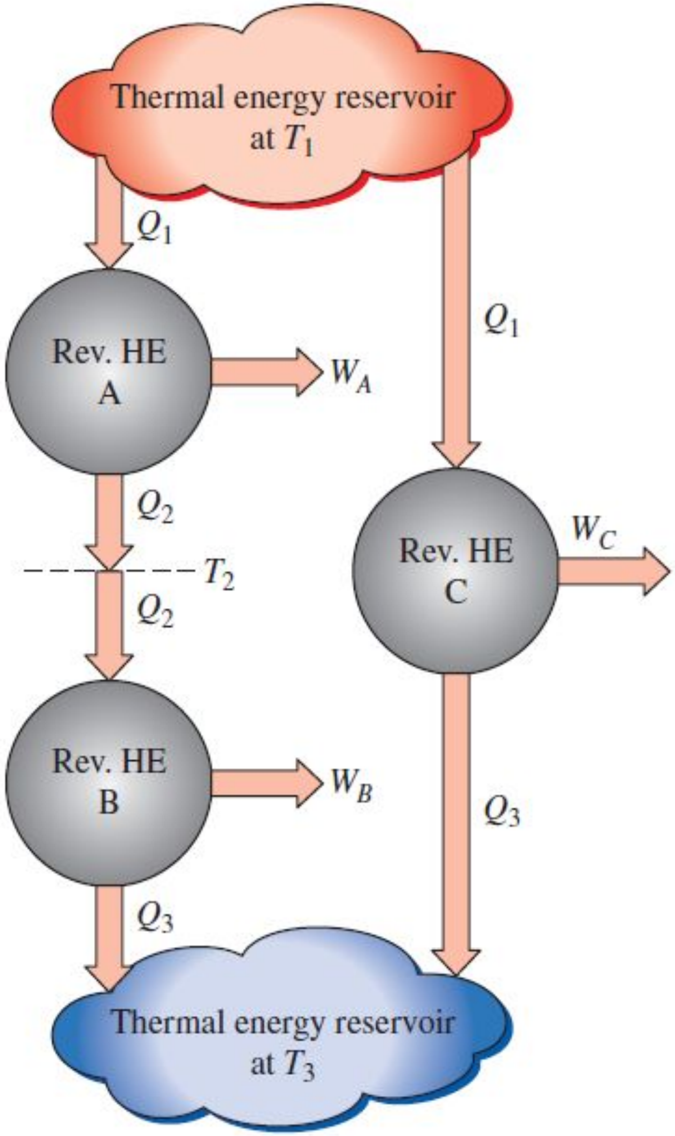


FIGURE 6–42
The arrangement of heat engines used to develop the thermodynamic temperature scale.

THE THERMODYNAMIC TEMPERATURE SCALE

$$\eta_{\text{th,rev}} = g(T_H, T_L) \qquad \frac{Q_H}{Q_L} = f(T_H, T_L)$$

$$\frac{Q_1}{Q_2} = f(T_1, T_2), \quad \frac{Q_2}{Q_3} = f(T_2, T_3), \quad \text{and} \quad \frac{Q_1}{Q_3} = f(T_1, T_3)$$

$$\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2}\frac{Q_2}{Q_3} \qquad f(T_1, T_3) = f(T_1, T_2)\cdot f(T_2, T_3)$$

$$f(T_1, T_2) = \frac{\phi(T_1)}{\phi(T_2)} \quad \text{and} \quad f(T_2, T_3) = \frac{\phi(T_2)}{\phi(T_3)}$$

$$\frac{Q_1}{Q_3} = f(T_1, T_3) = \frac{\phi(T_1)}{\phi(T_3)} \qquad \frac{Q_H}{Q_L} = \frac{\phi(T_H)}{\phi(T_L)}$$

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

Kelvin scale.

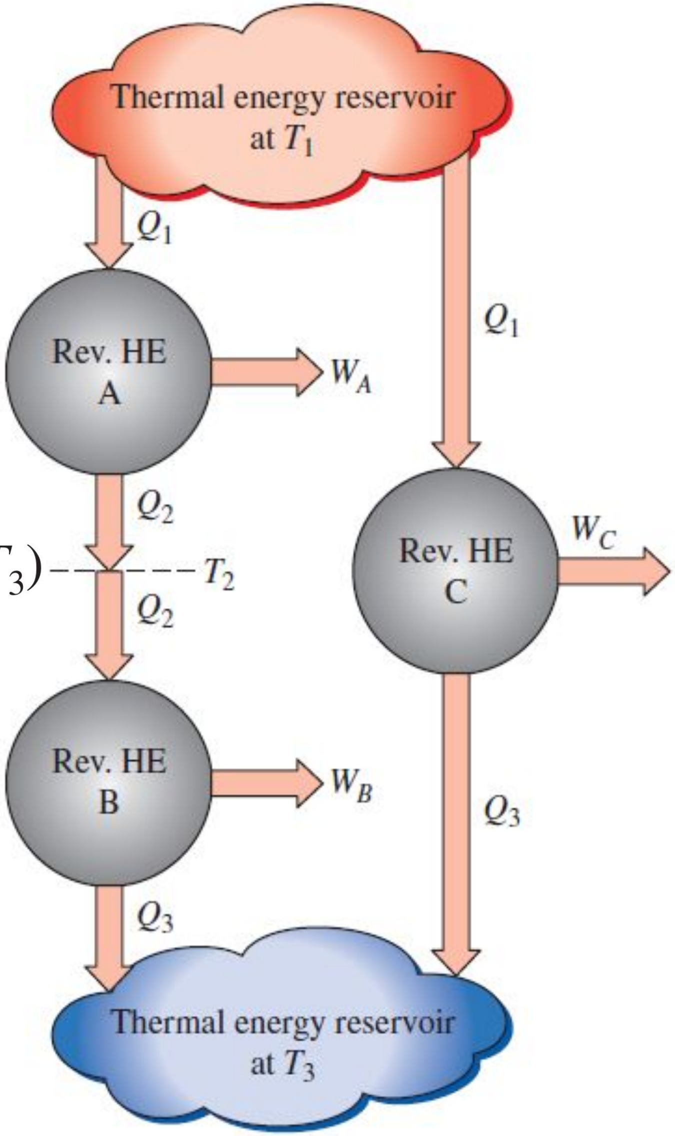


FIGURE 6–42
The arrangement of heat engines used to develop the thermodynamic temperature scale.

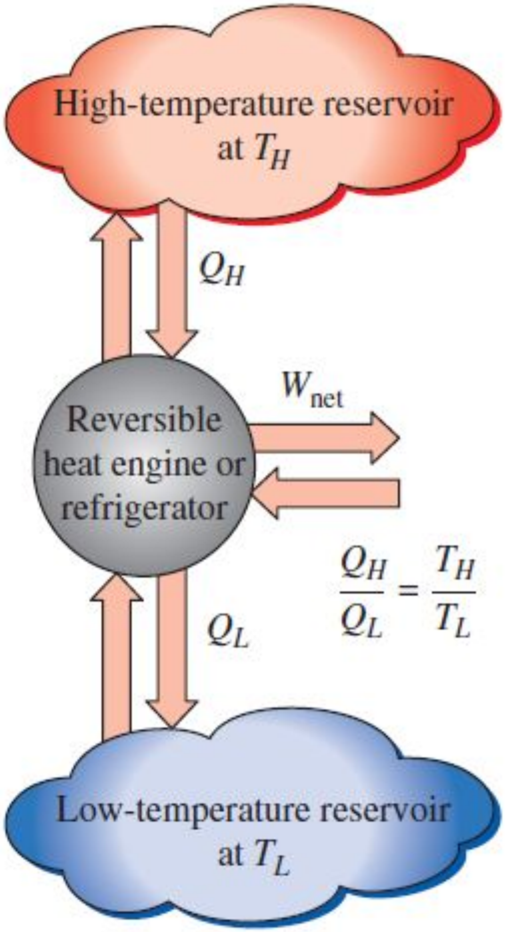


FIGURE 6–43
For reversible cycles, the heat transfer ratio Q_H/Q_L can be replaced by the absolute temperature ratio T_H/T_L.

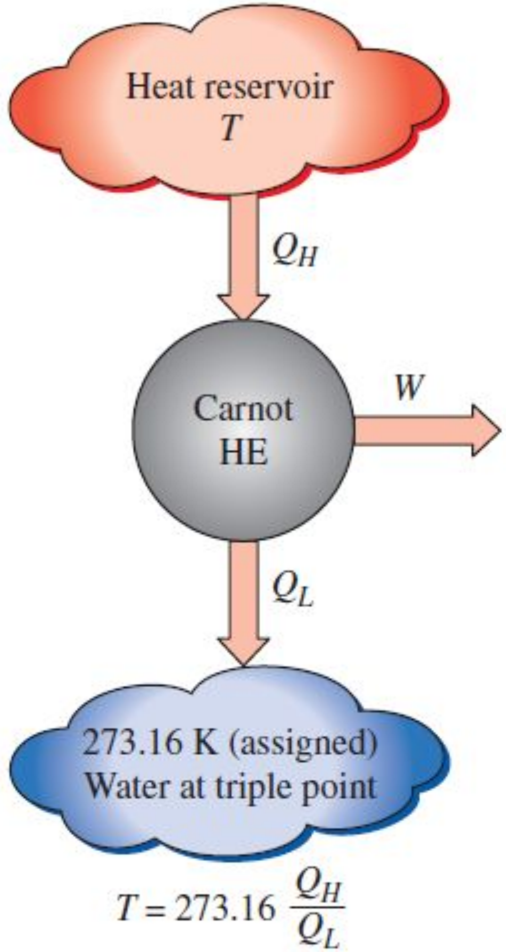


FIGURE 6–44
A conceptual experimental setup to determine thermodynamic temperatures on the Kelvin scale by measuring heat transfers Q_H and Q_L.

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

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

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

Any heat engine

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

Carnot heat engine

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

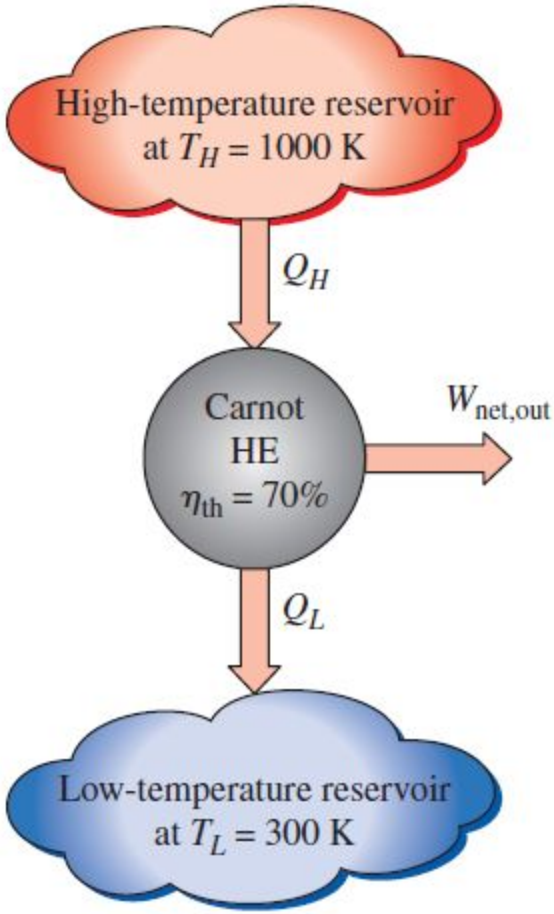


FIGURE 6–45
The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.

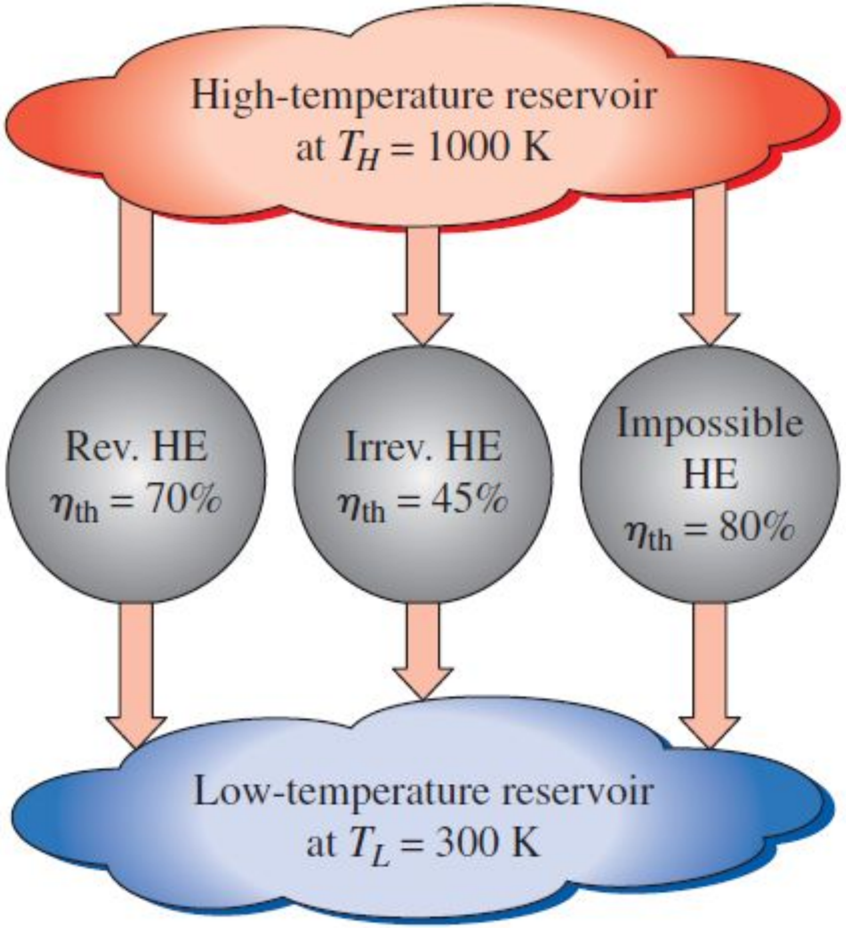
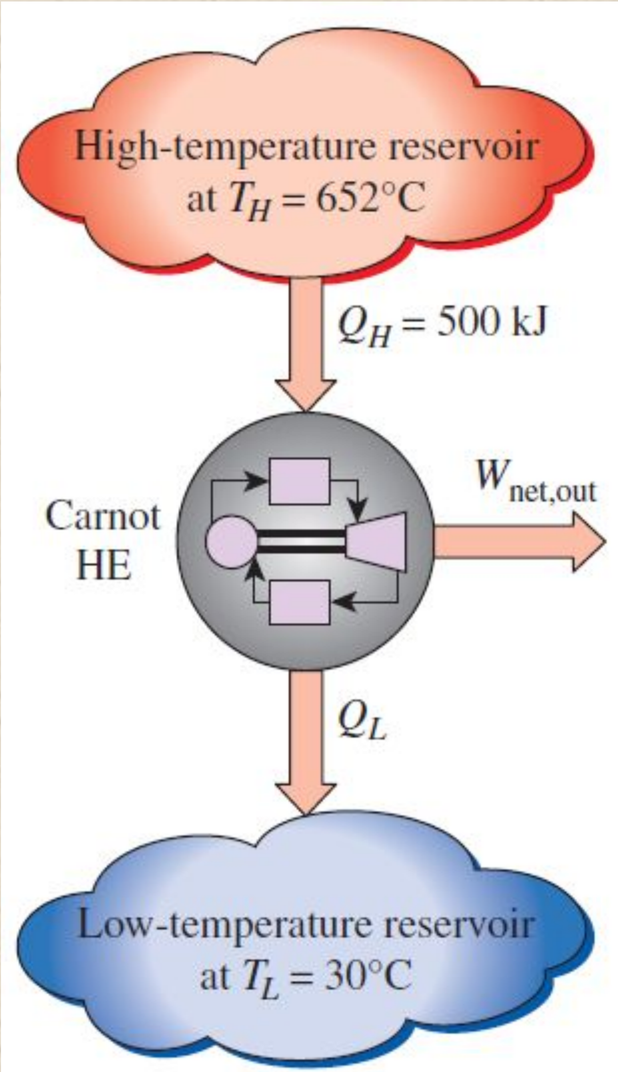


FIGURE 6–46

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

Analysis of a Carnot Heat Engine



$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{(30 + 273)\ K}{(652 + 273)\ K} = \mathbf{0.672}$$

$$Q_{L,rev} = \frac{T_L}{T_H} Q_{H,rev} = \frac{(30 + 273)\ K}{(652 + 273)\ K} (500\ kJ) = \mathbf{164\ kJ}$$