***Answer to Essential Question 15.7***: Decreasing the disorder of the room decreases its entropy. If the cleaning up process happened spontaneously that would violate the Second Law. However, in the system of you and the room, the decrease in entropy of the room is more than offset by the increase in entropy in your body, as measured by things like waste products that accumulated in your muscles as you did work. The room does not represent a closed system; examining a closed system (you and the room) we see that the Second Law of Thermodynamics is satisfied.

## *15-8 Heat Engines*

Heat engines use heat to do work. Examples are car engines and heat engines that run in reverse, such as refrigerators and air conditioners. All heat engines require two temperatures. Adding heat at a higher temperature expands the system, while removing it at a lower temperature contracts the system, re-setting the engine so that a new cycle can occur.

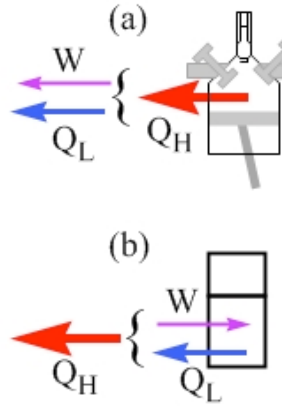


**Figure 15.20**: Energy flow diagrams. In (a), some heat from the cylinder of a car engine does useful work and the rest is discarded into the atmosphere. In (b), the combination of the heat removed from inside a refrigerator, and the work needed to extract it, is discarded into the room by the refrigerator's cooling coils.

Diagrams of the energy flow in a heat engine are shown in Figure 15.20. $Q_H$ is the magnitude of the heat added or removed at a higher temperature, while $Q_L$ is the magnitude of the heat added or removed at a lower temperature. $W$ is the magnitude of the work involved, which is negative for a cooling device.

The energy equation to accompany the diagram above (which is simply the First Law of Thermodynamics applied to a cycle, or a number of cycles) is:

$$Q_H - Q_L = W \, . \qquad \text{(Eq. 15.15: \textbf{Energy equation for a heat engine or cooling device})}$$

The efficiency, *e*, of a heat engine is the work done by the engine divided by the heat added to cause that work to be done:

$$e = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H} \, . \qquad \text{(Equation 15.16: \textbf{Efficiency for a heat engine})}$$

Can an ideal engine have an efficiency of 1, by eliminating losses from things like friction? No, in fact, as was proved by the French mathematician Sadi Carnot (1796 – 1832).

**EXPLORATION 15.8 – An ideal (Carnot) engine**

Carnot showed that an engine runs at maximum efficiency when it operates on the four-process cycle described in Table 15.5, and shown in the P-V diagram in Figure 15.21.

| Process | Description | Heat | $\Delta S$ |
|---|---|---|---|
| **1 → 2** | Isothermal expansion at $T_H$ | $+Q_H$ | $+Q_H/T_H$ |
| **2 → 3** | Adiabatic expansion to $T_L$ | 0 | 0 |
| **3 → 4** | Isothermal compression at $T_L$ | $-Q_L$ | $-Q_L/T_L$ |
| **4 → 1** | Adiabatic compression to $T_H$ | 0 | 0 |
| **Cycle** | The Carnot Cycle | $Q_H - Q_L$ | 0 |

**Table 15.5**: The sequence of processes in a Carnot cycle.

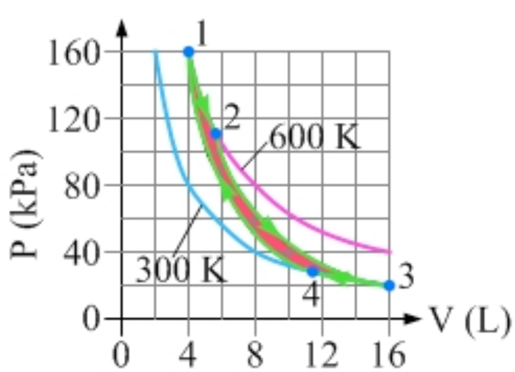


**Figure 15.21**: The P-V diagram for the Carnot cycle.

**Step 1 – *Equate the sum of the individual changes in entropy to the change in entropy for the cycle.*** Entropy is a state function. Because the cycle returns the system to its initial state the system returns to its original entropy. The change in entropy for a complete cycle is always zero:

$\sum \Delta S = 0$ which gives, in this case: $\frac{Q_H}{T_H} = \frac{Q_L}{T_L}$.

This gives: $\frac{T_L}{T_H} = \frac{Q_L}{Q_H}$. (Equation 15.17: **The Carnot relationship for an ideal engine**)

**Step 2 – *Write the efficiency equation in terms of temperatures.*** Substituting Equation 15.17 into the efficiency equation, Equation 15.16 gives the efficiency of an ideal engine:

$e_{ideal} = 1 - \frac{T_L}{T_H}$. (Equation 15.18: **Efficiency for an ideal engine**)

**Key ideas for an ideal engine:** The maximum efficiency of an engine is determined by the two temperatures the engine operates between. The third law of thermodynamics states that it is impossible to reach absolute zero, so even an ideal engine can never achieve 100% efficiency. **Related End-of-Chapter Exercises: 41 – 43 and 58.**

**EXAMPLE 15.8 – A heat pump**

If you heat your home using electric heat, 1000 J of electrical energy can be transformed into 1000 J of heat. An alternate heating system is a heat pump, which extracts heat from a lower-temperature region (outside the house) and transfers it to a higher-temperature region (inside the house). The work done by the heat pump is 1000 J, and the temperatures are $T_H = 17°\text{C} = 290\text{K}$ and $T_L = -23°\text{C} = 250\text{K}$. (a) Predict whether the maximum amount of heat delivered to the house in this situation is more than, less than, or equal to 1000 J. (b) Calculate this maximum heat.

**SOLUTION**

(a) Many people predict that the heat pump delivers less than 1000 J of heat to the house, perhaps because of the condition that the efficiency is less than 1. However, the heat pump can be viewed as a cooling device since it is cooling the outside – it acts like an air conditioner in reverse. The heat delivered to the house is $Q_H$, which from the energy-flow diagram in Figure 15.20 (b) is larger than $W$. Thus, the pump delivers more than 1000 J of heat to the house.

(b) To find the maximum possible amount of heat we will treat the heat pump as an ideal device, and apply the Carnot relationship (Equation 15.17). Re-arranging this equation gives:

$$Q_L = \frac{T_L}{T_H} Q_H .$$

Substituting this into Equation 15.15, $Q_H - Q_L = W$, gives:

$$Q_H - \frac{T_L}{T_H} Q_H = W$$

Solving for $Q_H$, the heat delivered to the house, gives:

$$Q_H = \frac{T_H}{T_H - T_L} W = \frac{290\text{K}}{290\text{K} - 250\text{K}} (1000 \text{ J}) = 7250 \text{ J} .$$

Thus, 1000 J of work extracts 6250 J of heat from the outside air, delivering a total of 7250 J of heat to the indoors. This is why heat pumps are far superior to electric heaters!

**Related End-of-Chapter Exercises: 44, 45, 59, 60.**