Chapter 11
Heat Engines and the Second Law of Thermodynamics
The laws of thermodynamics...are critical to making intelligent choices about energy in today's global economy.
What Is a Heat Engine?

How do heat engines work? What determines their efficiency?
Heat Engines

- A gasoline engine is a form of a heat engine.
  - Gasoline is mixed with air.
  - A spark ignites the mixture, which burns rapidly.
  - Heat is released from the fuel as it burns.
  - The heat causes the gases in the cylinder to expand, doing work on the piston.
  - The work done on the piston is transferred to the drive shaft and wheels.
Heat Engines

- The wheels push against the road.
- According to Newton’s third law, the road exerts a force on the tires, allowing the car to move forward.

- Not all the heat from burning fuel is converted to work done in moving the car.
  - The exhaust gases emerging from the tailpipe release heat into the environment.
  - Unused heat is a general feature of heat engines.
Heat Engines

- All heat engines share these main features of operation:
  - Thermal energy (heat) is introduced into the engine.
  - Some of this energy is converted to mechanical work.
  - Some heat (waste heat) is released into the environment at a temperature lower than the input temperature.

\[ Q_H = W + Q_C \]
Efficiency

- Efficiency is the ratio of the net work done by the engine to the amount of heat that must be supplied to accomplish this work.

\[ e = \frac{W}{Q_H} \]
A heat engine takes in 1200 J of heat from the high-temperature heat source in each cycle, and does 400 J of work in each cycle. What is the efficiency of this engine?

a) 33%
b) 40%
c) 66%

\[ Q_H = 1200 \text{ J} \]
\[ W = 400 \text{ J} \]
\[ e = \frac{W}{Q_H} \]
\[ = \frac{400 \text{ J}}{1200 \text{ J}} \]
\[ = \frac{1}{3} = 0.33 \]
\[ = 33\% \]
How much heat is released into the environment in each cycle?

a) 33 J  
b) 400 J  
c) 800 J  
d) 1200 J

\[ Q_C = Q_H - W \]
\[ = 1200 \text{ J} - 400 \text{ J} \]
\[ = 800 \text{ J} \]
The efficiency of a typical automobile engine is less than 30%.
- This seems to be wasting a lot of energy.
- What is the best efficiency we could achieve?
- What factors determine efficiency?

In analogy to water wheels, Carnot reasoned that the greatest efficiency of a heat engine would be obtained by taking all the input heat at a single high temperature and releasing all the unused heat at a single low temperature.
Carnot Engine and Carnot Cycle

- Carnot also reasoned that the processes should occur without undue turbulence.
  - The engine is completely **reversible**: it can be turned around and run the other way at any point in the cycle, because it is always near equilibrium.
  - This is Carnot’s ideal engine.
- The cycle devised by Carnot that an ideal engine would have to follow is called a **Carnot cycle**.
- An (ideal, not real) engine following this cycle is called a **Carnot engine**.
1. Heat flows into cylinder at temperature $T_H$. The fluid expands isothermally and does work on the piston.
2. The fluid continues to expand, adiabatically.
3. Work is done by the piston on the fluid, which undergoes an isothermal compression.
4. The fluid returns to its initial condition by an adiabatic compression.
Carnot Efficiency

- The efficiency of Carnot’s ideal engine is called the **Carnot efficiency** and is given by:

\[ e_C = \frac{T_H - T_C}{T_H} \]

- This is the **maximum efficiency possible** for any engine taking in heat from a reservoir at absolute temperature \( T_H \) and releasing heat to a reservoir at temperature \( T_C \).

- Even Carnot’s ideal engine is less than 100% efficient.
A steam turbine takes in steam at a temperature of 400°C and releases steam to the condenser at a temperature of 120°C. What is the Carnot efficiency for this engine?

a) 30%
b) 41.6%
c) 58.4%
d) 70%

\[ T_H = 400°C = 673 \text{ K} \]
\[ T_C = 120°C = 393 \text{ K} \]
\[ e_C = \frac{(T_H - T_C)}{T_H} \]
\[ = \frac{(673 \text{ K} - 393 \text{ K})}{673 \text{ K}} \]
\[ = \frac{280 \text{ K}}{673 \text{ K}} \]
\[ = 0.416 = 41.6\% \]
If the turbine takes in 500 kJ of heat in each cycle, what is the maximum amount of work that could be generated by the turbine in each cycle?

\[
Q_H = 500 \text{ kJ} \\
e = \frac{W}{Q_H}, \\
\text{so } W = e Q_H \\
= (0.416)(500 \text{ kJ}) \\
= 208 \text{ kJ}
\]

a) 0.83 J
b) 16.64 kJ
c) 28 kJ
d) 208 kJ
Second Law of Thermodynamics

- No engine, working in a continuous cycle, can take heat from a reservoir at a single temperature and convert that heat completely to work.

- Therefore, no engine can have a greater efficiency than a Carnot engine operating between the same two temperatures.
An engine with an efficiency greater than the Carnot engine would produce a greater amount of work than the Carnot engine, for the same amount of heat input $Q_H$.

Some of this work could be used to run the Carnot engine in reverse, returning the heat released by the first engine to the higher-temperature reservoir.
The remaining work $W_{\text{excess}}$ would be available for external use, and no heat would end up in the lower-temperature reservoir.

The two engines would take a small quantity of heat from the higher-temperature reservoir and convert it completely to work.

This would violate the second law of thermodynamics.
If a heat engine is run in reverse, then work $W$ is done on the engine as heat $Q_C$ is removed from the lower-temperature reservoir and a greater quantity of heat $Q_H$ is released to the higher-temperature reservoir.

A device that moves heat from a cooler reservoir to a warmer reservoir by means of work supplied from some external source is called a **heat pump**.
The first law of thermodynamics requires that, for a complete cycle, the heat released at the higher temperature must equal the energy put into the engine in the form of both heat and work.

The engine returns to its initial condition at the end of each cycle; the internal energy of the engine does not change.

More heat is released at the higher temperature than was taken in at the lower temperature.

\[ W + Q_C = Q_H \]
A heat pump uses 200 J of work to remove 300 J of heat from the lower-temperature reservoir. How much heat would be delivered to the higher-temperature reservoir?

a) 100 J  
b) 200 J  
c) 300 J  
d) 500 J

\[ W = 200 \text{ J} \]
\[ Q_C = 300 \text{ J} \]
\[ Q_H = W + Q_C \]
\[ = 200 \text{ J} + 300 \text{ J} \]
\[ = 500 \text{ J} \]
A refrigerator is also a form of a heat pump.

It also moves heat from a cooler reservoir to a warmer reservoir by means of work supplied from some external source.

It keeps food cold by pumping heat out of the cooler interior of the refrigerator into the warmer room.

An electric motor or gas-powered engine does the necessary work.
A television commercial shows a couple in the middle of a heat wave, discussing buying an air conditioner. The woman is standing in front of the open door of the refrigerator, in an obvious attempt to cool off.

- Is this a good idea or a bad idea, as far as their electric bill is concerned?
- Will this at least achieve the women’s desired result (keeping cool) regardless of how much it costs?
- Short of buying an air conditioner, what could they do with the refrigerator to reduce the heat in the kitchen?
While a refrigerator is a form of heat pump, the term *heat pump* usually refers to a device that heats a building by pumping heat from the colder outdoors to the warmer interior.

An electric motor does the work needed to run the pump.

The amount of heat available to heat the house is greater than the work supplied:

\[ W + Q_C = Q_H \]

We can get a larger amount of heat from the heat pump than by converting the electrical energy directly to heat (*often 2-3 times as much*).
A heat pump heats a house by exchanging heat in an outside coil and transferring that heat to another coil inside, which releases heat to the air inside the building.

Many heat pumps are designed to pump heat in either direction, acting as air conditioners in the summer.

Most air conditioners are heat pumps that pump heat from inside a building to the warmer exterior.

Heat pumps are most effective for heating houses in climates where the temperature difference is not too great.
A television show tested the effectiveness of a product claiming to be “the world’s smallest air conditioner.” It was actually a small hand-held battery-powered fan, and the test was done by a person in a closed glass-walled phone booth.

- Is this battery-powered fan operating as a heat pump?
- If the person has a normal body temperature, and the sun is shining, would you expect the phone booth’s temperature to increase or decrease during the test?
- If there was nobody inside the booth and the sun was not shining (no heat going into or out of the phone booth) would you expect the temperature to increase or decrease during the test?
Another Statement of The Second Law of Thermodynamics

- Heat has a natural tendency to flow from hotter objects to colder objects. This can be expressed in a second statement of the second law of thermodynamics:

- Heat will not flow from a colder body to a hotter body unless some other process is also involved.

- For example, work can be used to pump heat against its usual direction of flow.
If heat could flow from the colder to the hotter reservoir without any work, heat released by the heat engine on the right side of the diagram could flow back to the hotter reservoir.

Some heat could then be removed from the hotter reservoir and converted completely to work, without adding heat to the colder reservoir.

This would violate the second law of thermodynamics.
Entropy

- Heat can be removed from a high-temperature source either by spontaneous flow to a low-temperature reservoir or by being used to run a heat engine.
- If the engine is a Carnot engine, the process is completely **reversible** and the maximum possible work has been obtained from the available heat.
If the heat simply flows from hot to cold spontaneously, the process is **irreversible** and the energy is not converted to useful work.

In the irreversible process, **we lose some ability to do useful work**.

**Entropy** is the quantity that describes the extent of this loss.

- Entropy is sometimes defined as *a measure of the disorder of the system*.
- The entropy of a system increases any time the disorder or randomness of the system increases.
Entropy remains constant in reversible processes but increases in irreversible processes.

- The entropy of a system decreases only if it interacts with some other system whose entropy is increased in the process.
  - This happens, for example, in the growth and development of biological organisms.

- The entropy of the universe or of an isolated system can only increase or remain constant. Its entropy can never decrease.
- The thermal energy of a gas consists of the kinetic energy of the molecules.
- The velocities of these molecules are randomly directed. Only some of them move in the proper direction to push the piston to produce work.
- The basic disorganization of heat energy is responsible for the limitations encompassed by the three statements of the second law.
- The natural tendency of entropy to increase can only be countered by introducing energy into the system:
  - For example, solar energy to support biological processes on earth.
  - For example, work done to organize a room’s clutter.
Thermal Power Plants and Energy Resources

- The most common way of producing electric power in this country is a *thermal power plant* that uses some form of heat engine, whether fueled by coal, oil, or natural gas (fossil fuels).
- Thermodynamics plays an extremely important role in any discussion of the use of energy.
- As worldwide economic development continues and fossil-fuel resources are depleted, questions of the optimal uses of energy resources become critical.
- *Wise decisions depend on the participation of an informed, scientifically literate citizenry.*
1. Fossil fuel (coal, oil, natural gas) is burned to release heat that causes the temperature of water and steam to increase.
Thermal-Electric Power Plant

2. Hot steam is run through a turbine (a heat engine) that turns a shaft connected to an electric generator.
3. Electricity is transmitted through power lines to consumers.
Because the steam turbine is a heat engine, its efficiency is inherently limited by the second law of thermodynamics.

- Any real engine involves some irreversible processes and so must fall short of the ideal conditions of a completely reversible Carnot engine.
- A steam turbine comes closer to the ideal than the highly turbulent internal-combustion engine.

The maximum possible efficiency is dictated by the temperature difference between the hot and cold reservoirs.

- Heating the steam to as high a temperature as possible is advantageous.
- The exhaust temperature will be near the boiling point of water, where the steam condenses to water.
In practice, only about half the thermal energy released in burning coal or oil is converted to mechanical work or electrical energy.

The rest must be released into the environment at temperatures too low for running heat engines.

Cooling towers transfer this waste heat into the atmosphere, or heated water is released into a river.
Alternatives to Fossil Fuels

- Nuclear power plants
  - Lower thermal efficiencies
  - More heat released into environment
  - No carbon dioxide and other greenhouse gases released
  - Nuclear waste must be processed and disposed of
Geothermal Energy

- Heat from the interior of the earth, such as hot springs and geysers.
- Water temperature not hot enough to yield a high efficiency.
- **Sun as energy source**
  - *Warm ocean currents*
  - *Solar power*

Mirrors focus sunlight to heat a central boiler at a solar-thermal power plant.
High-Grade and Low-Grade Heat

- The temperature difference between the hot reservoir and the cold reservoir determine the maximum possible efficiency.
- **High-grade heat** is heat at temperatures around 500°C or higher, and is more useful than heat at lower temperatures.
- **Low-grade heat**, around 100°C or lower, can produce work but with considerably lower efficiency.
  - Low-grade heat is better used for purposes like heating homes or buildings/
  - Much low-grade heat, such as the low-temperature heat released from power plants, goes to waste because it is not economical to transport it to where it might be utilized.
- The main advantage of electrical energy is that it is easily transported.
  - It can be converted to mechanical energy by efficient electric motors.
  - It can also be converted back to heat, but this is a very inefficient use of high-grade heat (in the initial production of the electrical energy).
Perpetual Motion and Energy Fluids

- A perpetual-motion machine of the first kind is a proposed engine of machine that would violate the first law of thermodynamics.
- It puts out more energy as work or heat than it takes in.
- Buyer beware:
  - Where is the energy coming from?
  - How can the machine put more energy out than went in?
A *perpetual-motion machine of the second kind* does not put more energy out than goes in. Instead, it may claim to be able to take heat from a reservoir at a single temperature and convert it completely to work. This violates the second law of thermodynamics: some heat must be released into a lower-temperature reservoir. Or, it may simply claim a higher efficiency than the Carnot efficiency (for the available temperature difference). Such claims may be put forward by well-intentioned but misguided persons. Some are promoted by charlatans.
Would it be possible to generate electricity by running a water wheel with water drained from the bottom of a pond returning to the top of the pond?
Is it possible for a heat engine to operate as shown in the following diagram?

- a) Yes
- b) No, not ever
- c) Only if it is a Carnot engine
- d) It depends

This is a perpetual-motion machine of the second kind. According to the second law of thermodynamics, heat can never be completely converted to work without some waste heat released.
Is it possible for a heat engine to operate as shown in the following diagram?

a) Yes  
b) No, not ever  
c) Only if it is a Carnot engine  
d) It depends

This is a perpetual-motion machine of the first kind. According to the first law of thermodynamics, you can never get out more energy in work than you put in as heat.
Is it possible for a heat engine to operate as shown in the following diagram?

a) Yes  
b) No, not ever  
c) Only if it is a Carnot engine  
d) It depends

This extracts heat from a single source, performs work and puts the remaining heat energy back in the original source of heat. The net effect is to extract heat from a single source and convert it all to work, which is a violation of Kelvin's statement of the second law.
Is it possible for a heat pump to operate as shown in the following diagram?

a) Yes
b) No, not ever
c) Only if it is a Carnot engine
d) It depends

Work must be performed in order to remove heat from the cool reservoir and move it to the hot reservoir.
Is it possible for a heat pump to operate as shown in the following diagram?

- a) Yes
- b) No, not ever
- c) Only if it is a Carnot engine
- d) It depends

This violates the first law of thermodynamics. Work is being done to transfer heat from the cooler reservoir to the hotter reservoir. However, more heat is being withdrawn and more work is being done than is being transferred.
Is it possible for a heat pump to operate as shown in the following diagram?

a) Yes  
b) No, not ever  
c) Only if it is a Carnot engine  
d) It depends

This diagram is correct!!!  
More heat is transferred to the hot reservoir than is taken in from the cold one, with work being done.