The Language of Physics

Thermodynamics
The study of the relationships between heat, internal energy, and the mechanical work performed by a system. The system is usually a heat engine of some kind (p. 479).

Work
The work done by a gas during expansion is positive and the work done by a gas during compression is negative. The work done is equal to the area under the curve in a *p-V* diagram. The work done depends on the thermodynamic path taken in the *p-V* diagram (p. 480).

Cyclic process
A process that runs in a cycle eventually returning to where it started from. The net work done by the system during a cyclic process is equal to the area enclosed by the cyclic thermodynamic path in a *p-V* diagram. The net work is positive if the cycle proceeds clockwise, and negative if the cycle proceeds counterclockwise on the *p-V* diagram. The total change in internal energy around the entire cycle is equal to zero. The energy for the net work done by the system comes from the net heat applied to the system (p. 480).

Isobaric process
A process that takes place at a constant pressure (p. 482).

Isochoric or isometric processes
A process that takes place at constant volume. The heat added to a system during an isochoric process shows up as an increase in the internal energy of the system (p. 482).

Isothermal process
A process that takes place at constant temperature (p. 482).

Molecular mass
The molecular mass of any substance is equal to the mass of one molecule of that substance times the total number of molecules in one mole of the substance (Avogadro's number). *Thus, the molecular mass of any substance is equal to the mass of one mole of that substance.* Hence, the mass of a gas is equal to the number of moles of a gas times the molecular mass of the gas (p. 484).

Molar specific heat
The product of the specific heat of a substance and its molecular mass (p. 484).

Heat in a thermodynamic process
The heat absorbed or liberated in a thermodynamic process depends on the path that is followed in a *p-V* diagram. Thus, heat, like work, is path dependent. Heat is always positive when it is added to the system and negative when it is removed from the system (p. 484).

Internal energy of a gas
The internal energy of a gas is equal to the sum of the kinetic energy of all the molecules of a gas. A change in temperature is associated with a change in the internal energy of a gas. Hence, an isothermal expansion occurs at constant internal energy. Regardless of the path chosen between two points in a *p-V* diagram, the change in internal energy is always the same. Thus, the internal energy of the system is independent of the path taken in a *p-V* diagram; it depends only on the initial and final states of the thermodynamic system (p. 485).

The first law of thermodynamics
The heat added to a system will show up either as a change in internal energy of the system or as work performed by the system. It is also stated in the form: the change in the internal energy of the system equals the heat added to the system minus the work done by the system on the outside environment. The first law is really a statement of the law of conservation of energy applied to a thermodynamic system (p. 487).

Efficiency
The efficiency of an engine can be defined in terms of what we get out of the system compared to what we put into the system. It is thus equal to the ratio of the work performed by the system to the heat put into the system. It is desirable to make the efficiency of an engine as high as possible (p. 491).

Adiabatic process
A process that occurs without an exchange of heat between the system and its environment. That is, heat is neither added nor taken away from the system during the process (p. 492).

Otto cycle
A thermodynamic cycle that is approximated in the operation of the gasoline engine (p. 495).

Ideal heat engine
An idealized engine that shows the main characteristics of all engines, namely, every engine absorbs heat from a source at high temperature, performs some amount of mechanical work, and then rejects some heat at a lower temperature (p. 495).

Refrigerator
A heat engine working in reverse. That is, work is done on the refrigerator, thereby extracting a quantity of heat from a low-temperature reservoir and exhausting a large quantity of heat to a hot reservoir (p. 496).

Carnot cycle
A thermodynamic cycle of a Carnot engine, consisting of two isothermal and two adiabatic paths in a *p-V* diagram. The Carnot engine is the most efficient of all engines (p. 496).

The second law of thermodynamics
The second law of thermodynamics tells us which processes are possible and which are not. The concept of entropy is introduced to give a quantitative basis for the second law. It is equal to the ratio of the heat added to the system to the absolute temperature of the system, when a thermodynamic system changes from one equilibrium state to another along a reversible path. In an isolated system, the system always changes from values of low entropy to values of high entropy, and only those processes are possible for which the entropy of the system increases or remains a constant (p. 498).

Kelvin-Planck statement of the second law of thermodynamics
No process is possible whose sole result is the absorption of heat from a reservoir at a single temperature and the conversion of this heat energy completely into mechanical work (p. 498).

Clausius statement of the second law of thermodynamics
No process is possible whose sole result is the transfer of heat from a cooler to a hotter body (p. 499).

Summary of Important Equations

Work done by a gas
$W = p\Delta V$ (17.5)

Mass of the gas
$m = m_0 N_A n$ (17.14)

Molecular mass
$M = m_0 N_A$ (17.15)

Mass of the gas
$m = nM$ (17.16)

Molar specific heat
$C = Mc$ (17.18)

Heat absorbed or liberated by a gas at constant volume
$Q = nC_v\Delta T$ (17.20)

Heat absorbed or liberated by a gas at constant pressure
$Q = nC_p\Delta T$ (17.21)

Internal energy of an ideal gas
$U = \frac{3}{2}nRT$ (17.23)

Change in internal energy of an ideal gas
$\Delta U = \frac{3}{2}nR\Delta T$ (17.24)

Change in internal energy of an ideal gas
$\Delta U = nC_v\Delta T$ (17.28)

Molar specific heat at constant volume
$C_v = \frac{3}{2}R$ (17.29)

Molar specific heat at constant pressure
$C_p = \frac{5}{2}R$ (17.42)

First law of thermodynamics
$\Delta U = Q - W$ (17.31)

Adiabatic process
$Q = 0$

First law for adiabatic process
$W = -\Delta U$ (17.44)

Isochoric process
$\Delta V = 0$

First law for isochoric process
$Q = \Delta U$ (17.47)

Isobaric process
$\Delta p = 0$

Cyclic process
$\Delta U = 0$

First law for cyclic process
$W = Q$ (17.48)

Efficiency of any engine

$$\text{Eff} = \frac{W}{Q_{in}} = \frac{W}{Q_H}$$

$$\text{Eff} = \frac{Q_H - Q_C}{Q_H} \quad (17.50)$$

$$\text{Eff} = 1 - \frac{Q_C}{Q_H} \quad (17.51)$$

Efficiency of a Carnot engine

$$\text{Eff} = 1 - \frac{T_C}{T_H} \quad (17.55)$$

Entropy

$$\Delta S = \frac{\Delta Q}{T} \quad (17.56)$$

$$S = k \ln P \quad (17.58)$$

Questions for Chapter 17

1. Discuss the difference between the work done by the gas and the work done on the gas in any thermodynamic process.
2. Why is the work done in a thermodynamic process a function of the path traversed in the p-V diagram?
3. Define the following processes: isobaric, isothermal, isochoric, adiabatic, cyclic, and isoentropic.
4. How is it possible that a solid and a liquid have one value for the specific heat and a gas can have an infinite number of specific heats?
5. Discuss the first and second laws of thermodynamics.
6. Describe what is meant by the statement, "the internal energy of a thermodynamic system is conservative."
7. Figure 17.7 shows a plot of isotherms and adiabats on a p-V diagram. Explain why the adiabats have a steeper slope.

†8. Discuss the thermodynamic process in a diesel engine, and draw the process on a p-V diagram.

†9. Use the first law of thermodynamics to describe a solar heating system.

10. Can you use a home refrigerator to cool the home in the summer by leaving the door of the refrigerator open?

†11. Why is a heat pump not very efficient in very cold climates?

†12. Show how equation 17.54 could be used as the basis of a temperature scale.

13. Is it possible to connect a heat engine to a refrigerator such that the work done by the engine is used to drive the refrigerator, and the waste heat from the refrigerator is then given to the engine, to drive the engine thus making a perpetual motion machine?
14. Discuss the concept of entropy and how it can be used to determine if a thermodynamic process is possible.

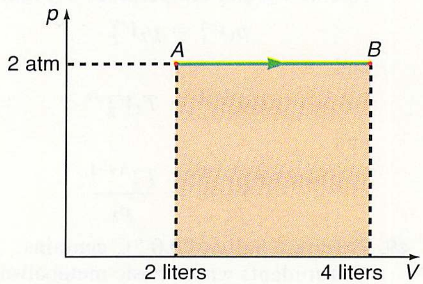
†15. Discuss the statements: (a) entropy is sometimes called time's arrow and (b) the universe will end in a heat death when it reaches its state of maximum entropy.

Problems for Chapter 17

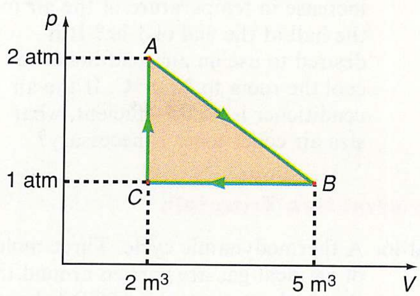
17.2 The Concept of Work Applied to a Thermodynamic System

1. How much work is done by an ideal gas when it expands at constant atmospheric pressure from a volume of 0.027 m^3 to a volume of 1.00 m^3?

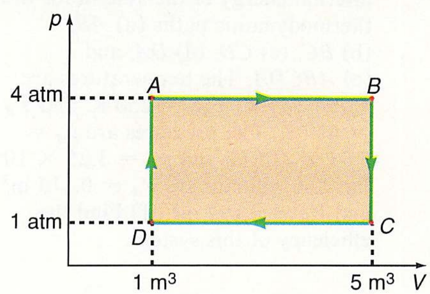
2. What is the area of the cross-hatched area in the *p-V* diagram? What is the work done in going from *A* to *B*?



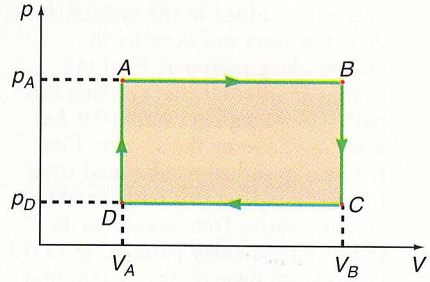
3. What is the net work done in the triangular cycle *ABC*?



4. How much work is done in the cycle *ABCDA*?



5. One mole of an ideal gas goes through the cycle shown. If $p_A = 2.00 \times 10^5$ Pa, $p_D = 5.00 \times 10^4$ Pa, $V_B = 2.00$ m^3, and $V_A = 0.500$ m^3, find the work done along the paths (a) *AB*, (b) *BC*, (c) *CD*, (d) *DA*, and (e) *ABCDA*.



17.3 Heat Added to or Removed from a Thermodynamic System

6. What is the mass of 4.00 moles of He gas?

7. Find the amount of heat required to raise the temperature of 5.00 moles of He, 10.0 °C, at constant volume.

8. Find the amount of heat required to raise the temperature of 5.00 moles of He, 10.0 °C, at constant pressure.

9. Compute the amount of heat absorbed when one mole of a monatomic gas, at a temperature of 200 K, rises to a temperature of 400 K (a) isochorically and (b) isobaricly.

17.4 The First Law of Thermodynamics

10. What is the total internal energy of 3.00 moles of an ideal gas at (a) 273 K and (b) 300 K?

11. What is the change in internal energy of 3.00 moles of an ideal gas when it is heated from 273 K to 293 K?

12. Find the change in the internal energy of 1 mole of an ideal gas when heated from 300 K to 500 K.

13. In a thermodynamic system, 500 J of work are done and 200 J of heat are added. Find the change in the internal energy of the system.

14. In a certain process, the temperature rises from 50.0 °C to 150.0 °C as 1000 J of heat energy are added to 4 moles of an ideal gas. Find the work done by the gas during this process.

15. In a thermodynamic system, 200 J of work are done and 500 J of heat are added. Find the change in the internal energy of the system.

16. In a certain process with an ideal gas, the temperature drops from 120 °C to 80.0 °C as 2000 J of heat energy are removed from the system and 1000 J of work are done by the gas. Find the number of moles of the gas that are present.

17. Four moles of an ideal gas are carried through the cycle *ABCDA* of figure 17.6. If $T_D = 100$ K, $T_{AC} = T_A = T_C = 200$ K, $T_B = 400$ K, $p_A = 0.500 \times 10^5$ Pa, and $p_D = 2.50 \times 10^4$ Pa, use the ideal gas equation to determine the volumes V_A and V_B.

†18. In problem 17 find the work done, the heat lost or absorbed, and the change in internal energy of the gas for the paths (a) *AB*, (b) *BC*, (c) *CD*, (d) *DA*, and (e) *ABCDA*.

19. In a thermodynamic system, 700 J of work are done by the system while the internal energy drops by 450 J. Find the heat transferred to the gas during this process.

20. If 5.00 J of work are done by a refrigerator and 8.00 J of heat are exhausted into the hot reservoir, how much heat was removed from the cold reservoir?

21. A heat engine is operating at 40.0% efficiency. If 3.00 J of heat are added to the system, how much work is the engine capable of doing?

17.5 Some Special Cases of the First Law of Thermodynamics

22. If the temperature of 2.00 moles of an ideal gas increases by 40.0 K during an isochoric process, how much heat was added to the gas?

23. If 800 J of thermal energy are removed from 8 moles of an ideal gas during an isochoric process, find the change in temperature in degrees (a) Kelvin, (b) Celsius, and (c) Fahrenheit.

24. If 3.00 J of heat are added to a gas during an isothermal expansion, how much work is the system capable of doing during this process?

25. During an isothermal contraction, 55.0 J of work are done on an ideal gas. How much thermal energy was extracted from the gas during this process?

†26. A monatomic gas expands adiabatically to double its original volume. What is its final pressure in terms of its initial pressure?

†27. One mole of He gas at atmospheric pressure is compressed adiabatically from an initial temperature of 20.0 °C to a final temperature of 100 °C. Find the new pressure of the gas.

28. If 50.0 J of work are done on one mole of an ideal gas during an adiabatic compression, what is the temperature change of the gas?

17.6 The Gasoline Engine

†29. The crankshaft of a gasoline engine rotates at 1200 revolutions per minute. The area of each piston is 80.0 cm^2 and the length of the stroke is 13.0 cm. If the average pressure during the power stroke is 7.01×10^5 Pa, find the power developed in each cylinder. (*Hint:* remember that there is only one power stroke for every two revolutions of the crankshaft.)

17.7 The Ideal Heat Engine

30. An engine operates between room temperature of 20.0 °C and a cold reservoir at 5.00 °C. Find the maximum efficiency of such an engine.
31. What is the efficiency of a Carnot engine operating between temperatures of 300 K and 500 K?
32. A Carnot engine is working in reverse as a refrigerator. Find the coefficient of performance if the engine is operating between the temperatures −10.5 °C and 35.0 °C.
33. A Carnot refrigerator operates between −10.0 °C and 25.0 °C. Find how much work must be done per kcal of heat extracted.
34. Calculate the efficiency of an engine that absorbs 500 J of thermal energy while it does 250 J of work.

17.10 Entropy

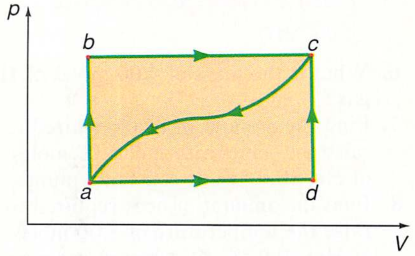
35. Find the change in entropy if 10.0 kg of ice at 0.00 °C is converted to water at +10.0 °C.
36. A gas expands adiabatically from 300 K to 350 K. Find the change in its entropy.

†37. Find the total change in entropy if 2.00 kg of ice at 0.00 °C is mixed with 25.0 kg of water at 20.0 °C.

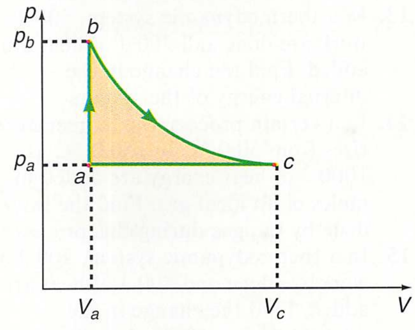
38. Find the change in entropy when 2.00 kg of steam at 110 °C is converted to water at 90.0 °C.
39. A gas expands isothermally and does 500 J of work. If the temperature of the gas is 35.0 °C, find its change in entropy.

Additional Problems

40. In the thermodynamic system shown in the diagram, (a) 50.0 J of thermal energy are added to the system, and 20.0 J of work are done by the system along path *abc*. Find the change in internal energy along this path. (b) Along path *adc*, 10.0 J of work are done by the system. Find the heat absorbed or liberated from the system along this path. (c) The system returns from state *c* to its initial state *a* along path *ca*. If 15.0 J of work are done on the system find the amount of heat absorbed or liberated by the system.



41. Draw the following process on a *p-V* diagram. First 8.00 m^3 of air at atmospheric pressure are compressed isothermally to a volume of 4.00 m^3. The gas then expands adiabatically to 8.00 m^3 and is then compressed isobaricly to 4.00 m^3.
42. In the diagram shown, one mole of an ideal gas is at atmospheric pressure and a temperature of 250 K at position *a*. (a) Find the volume of the gas at *a*. (b) The pressure of the gas is then doubled while the volume is kept constant. Find the temperature of the gas at position *b*. (c) The gas is then allowed to expand isothermally to position *c*. Find the volume of the gas at *c*.



†43. Repeat problem 42, but for part (c) let the gas expand adiabatically to atmospheric pressure. Find the volume of the gas at this point. Show this point on the diagram.

†44. It was stated in equation 17.45 that for an adiabatic process with an ideal gas,

$$pV^\gamma = \text{constant}$$

Show that when an ideal gas in an initial state, with pressure p_1, volume V_1, and temperature T_1, undergoes an adiabatic process to a final state that is described by pressure p_2, volume V_2, and temperature T_2, that

$$p_1V_1^\gamma = p_2V_2^\gamma$$

and

$$T_1V_1^{\gamma-1} = T_2V_2^{\gamma-1}$$

and

$$\frac{T_1^{\gamma/(\gamma-1)}}{p_1} = \frac{T_2^{\gamma/(\gamma-1)}}{p_2}$$

45. A lecture hall at 20.0 °C contains 100 students whose basic metabolism generates 100 kcal/hr of thermal energy. If the size of the hall is 15.0 m by 30.0 m by 4.00 m, what is the increase in temperature of the air in the hall at the end of 1 hr? It is desired to use an air conditioner to cool the room to 20.0 °C. If the air conditioner is 45.0% efficient, what size air conditioner is necessary?

Interactive Tutorials

46. A thermodynamic cycle. Three moles of an ideal gas are carried around the thermodynamic cycle *ABCDA* shown in figure 17.6. Find the work done, the heat lost or absorbed, and the internal energy of the system for the thermodynamic paths (a) *AB*, (b) *BC*, (c) *CD*, (d) *DA*, and (e) *ABCDA*. The temperatures are $T_D = 147$ K, $T_{AC} = 250$ K, and $T_B = 425$ K. The pressures are $p_A = 5.53 \times 10^4$ Pa and $p_D = 3.25 \times 10^4$ Pa. The volumes are $V_A = 0.113$ m^3 and $V_B = 0.192$ m^3. (f) Find the efficiency of this system.