Chapter 15 Laws of Thermodynamics

AP Physics B

December

Laws of Thermodynamics

- Zeroth Law of Thermodynamics:
  - Thermometer in equilibrium with system A
  - Thermometer in equilibrium with system B
  - → A and B must be in equilibrium
- transitive

Laws of Thermodynamics

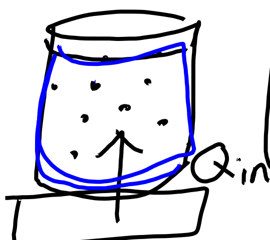
- **First Law**: Whenever heat flows into or out of a system, the gain or loss of thermal energy equals the amount of heat transferred.
  - Conservation of energy: something gives energy to something else.
  - Rub your hands together. Why did the temperature increase?
- **Second Law**: Heat naturally flows from hot to cold substance.
  - Winter time: warm air from house gives energy away to cold air outside.
  - Summer: Warm air outside gives energy to cold air inside.
  - Air conditioning: To pump cold air toward warm air, it needs work.
- **Third Law**: Nothing can reach Absolute Zero

Chapter Opening Question

- Thermal pollution. Part of the heat produced by burning fuel is not converted to electrical energy. The reason is:
  a) efficiency is higher if some heat is allowed to escape.
  b) Engineering technology has not yet reached the point where 100% waste heat recovery is possible.
  c) Some waste heat *must* be produced; this is a fundamental property of nature when converting heat to useful work
  d) The plants rely on fossil fuels, not nuclear fuel.
  e) None of the above

15.1 First Law: Conservation of Energy

- $$\overset{10\,J}{\underset{\text{heat}}{Q_{in}}} = \overset{8\,J}{\underset{\text{faster molecules}}{\Delta U}} + \overset{2\,J}{\underset{\text{done by system}}{W}}$$

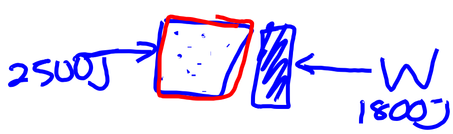


$$\boxed{\underset{\text{thermal energy}}{\Delta U} = \underset{\substack{>0 \\ \text{gas absorbs}}}{Q_{in}} - \underset{\substack{>0 \\ \text{by system}}}{W_{done}}}$$

- Q>0: system absorbs energy from temperature difference
- W>0: system does mechanical work (on container)
- ΔU = change in internal energy (PE + KE)

Ex1)

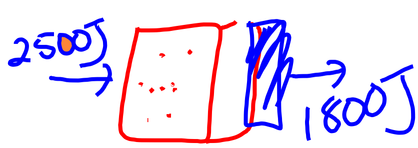
- 2500 J of heat is added to system
- 1800 J work done on system
- Change in system's internal energy?



4300J

$\Delta U = Q_{in} - W$
$= 2500 - (-1800)$

- A) 2500 J heat added, 1800 J work done by system
- Change in system's internal energy?



$\boxed{700\,J}$

If the System is moving and Has Potential energy too

- $\Delta KE + \Delta PE + \Delta U \quad = \quad Q \quad - \quad W$

  (total energy change) = input – output

- Example 2
  - 3.0 g bullet goes 400 m/s
  - Enters a tree
  - Exits the other side at 200 m/s
  - Where'd the KE go? How much energy was transferred?

15.1 First Law: conservation of Energy

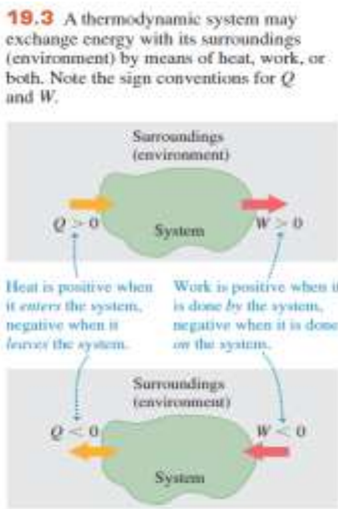
$$\Delta U \;=\; Q \;-\; W$$

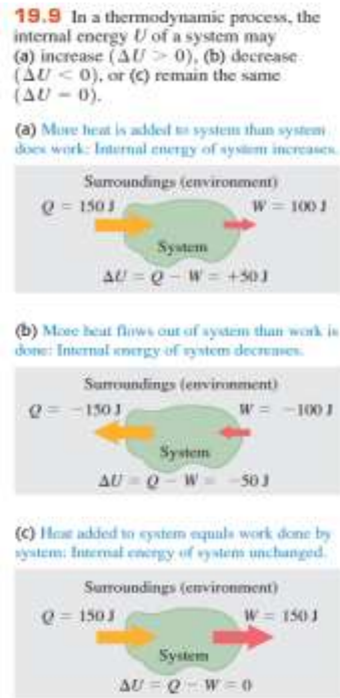
- State Variables: U, P, V, m~n, T
  - A system has a state
  - A system does not "have" heat or work, which is a *transfer* of energy

19.1 The popcorn in the pot is a thermodynamic system. In the thermodynamic process shown here, heat is added to the system, and the system does work on its surroundings to lift the lid of the pot.

15.1 First Law: conservation of En

$$\Delta U \;=\; Q \;-\; W$$

- 



15.1 First Law: conservation of Energy

- Hot coffee has been poured into an aluminum cup. Positive or negative?
  - Q with coffee as the system
  - Q with the cup as the system

- A block slides on a surface that has friction. Is the work done by the block positive or negative?

15.1 First Law: Conservation of Energy

$$\Delta U \;=\; Q \;-\; W$$

- Work depends on path! (Process/order by which the P, V, T state changed from one state to another state)
- Heat depends on path!
- ΔU does not depend on path!
  - Verified experimentally
  - U internal energy only depends

  on the present state P, V, T.

  It does not depend

  on how the system got there!

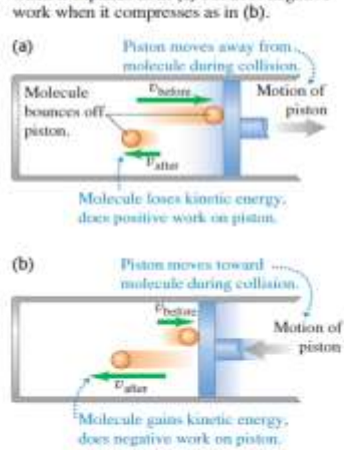
19.10 The internal energy of a cup of coffee depends on just its thermodynamic state—how much water and ground coffee it contains, and what its temperature is. It does not depend on the history of how the coffee was prepared—that is, the thermodynamic path that led to its current state.

- U = <u>internal</u> energy
  - KE + PE of all molecules <u>in</u> system
  - Putting a glass of water on a high shelf does not increase U since the water molecules' interactions are not affected.

15.2 Work Done During Volume Changes

- Gas in cylinder with a movable piston
  - Seen in internal-combustion engines, steam engines, compressors in refrigerators and air conditioners
  - No heat input example:
    a) gas expands V↑, W>0, ΔU<0
    b) Gas gets compressed V, W<0, ΔU>0

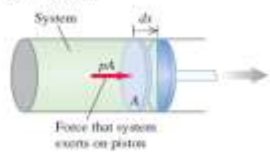
19.4 A molecule striking a piston (a) does positive work if the piston is moving away from the molecule and (b) does negative work if the piston is moving toward the molecule. Hence a gas does positive work when it expands as in (a) but does negative work when it compresses as in (b).



15.2 Work Done During Volume Changes

- System does work

19.5 The infinitesimal work done by the system during the small expansion dx is $dW = pA\,dx$.



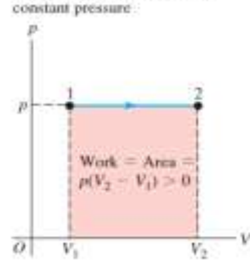
P = constant

W = Fd = PA Δx = P ΔV

$$W = \int_{V_1}^{V_2} p\,dV \qquad \text{(work done in a volume change)}$$

= area under the PV curve

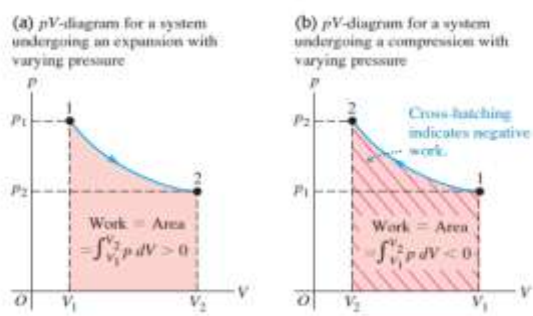
(c) pV-diagram for a system undergoing an expansion with constant pressure



15.2 Work Done During Volume Changes

- System does work

19.6 The work done equals the area under the curve on a pV-diagram.



Expand. Work done **by** system

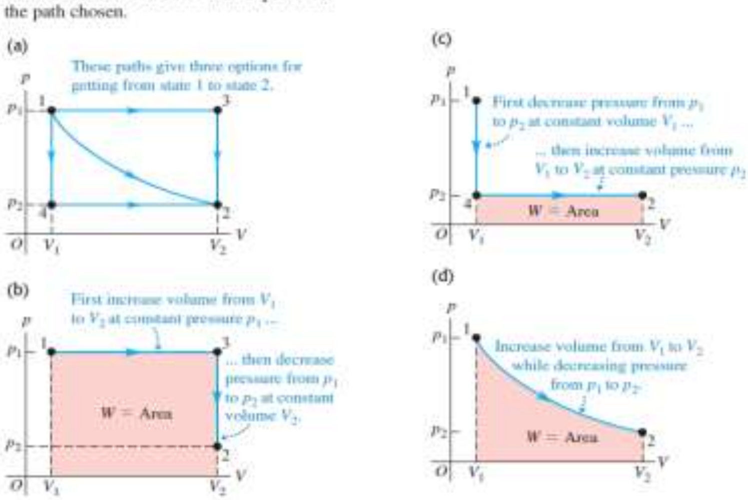
Compress. Work done **on** system

15.2 Work Done During Volume Changes

- **Test Your Understanding of Section 19.2** A quantity of ideal gas undergoes an expansion that increases its volume from V_1 to $V_2 = 2V_1$. The final pressure of the gas is p_2. Does the gas do more work on its surroundings if the expansion is at constant *pressure* or at constant *temperature*? (i) constant pressure; (ii) constant temperature; (iii) the same amount of work is done in both cases; (iv) not enough information is given to decide.

15.2 Work Depends on Path $\quad \Delta U = Q - W$

- **19.7** The work done by a system during a transition between two states depends on the path chosen.

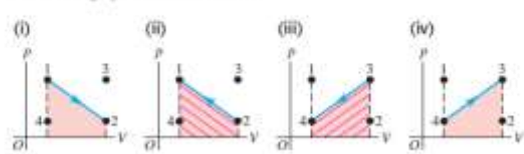


15.2 Work Depends on Path $\Delta U = Q - W$

Test Your Understanding of Section 19.3 The system described in Fig. 19.7a undergoes four different thermodynamic processes. Each process is represented in a pV-diagram as a straight line from the initial state to the final state. (These processes are different from those shown in the pV-diagrams of Fig. 19.7.) Rank the processes in order of the amount of work done by the system, from the most positive to the most negative. (i) $1 \rightarrow 2$; (ii) $2 \rightarrow 1$; (iii) $3 \rightarrow 4$; (iv) $4 \rightarrow 3$.

15.2 Work Depends on Path $\Delta U = Q - W$

- **19.3 Answer: (i) and (iv) (tie), (ii) and (iii) (tie)** The accompanying figure shows the pV-diagrams for each of the four processes. The trapezoidal area under the curve, and hence the absolute value of the work, is the same in all four cases. In cases (i) and (iv) the volume increases, so the system does positive work as it expands against its surroundings. In cases (ii) and (iii) the volume decreases, so the system does negative work (shown by cross-hatching) as the surroundings push inward on it.



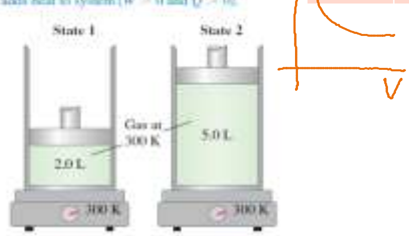
15.2 Heat Depends on Path $\Delta U = Q - W$

a)	b)

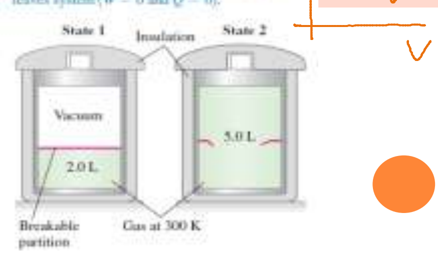
• Heat up slowly
• (since gas does work, need heat input to maintain temperature)
• $\Delta U = 0$, Qin>0 → W>0 (isothermal)
(cannot for heat engine)
	• Vacuum.
	• Free expansion
	• W = 0 since no volume change.
	• Q = 0 since isolated
	• $\Delta U = 0$ (ideal or not)
	  • (ideal gas, no temperature change. U = 3/2nRT)
	  • (non-ideal gas, temperature drops since U = KE↓ + (PE↑ farther, less attraction)

19.8 (a) Slow, controlled isothermal expansion of a gas from an initial state 1 to a final state 2 with the same temperature but lower pressure. (b) Rapid, uncontrolled expansion of the same gas starting at the same state 1 and ending at the same state 2.

(a) System does work on piston; hot plate adds heat to system ($W > 0$ and $Q > 0$).

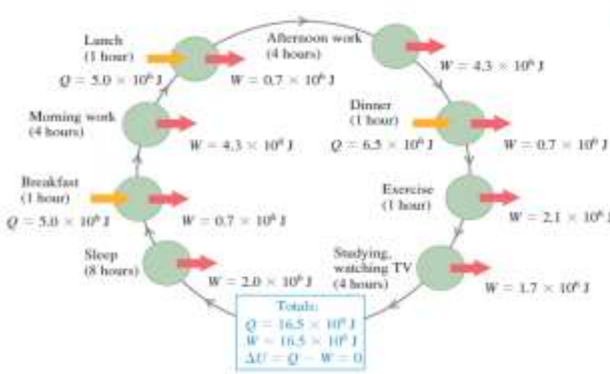


(b) System does no work; no heat enters or leaves system ($W = 0$ and $Q = 0$).



Vocab

- Cyclic Process: initial and final states are the same
  - U1 = U2, $\Delta U = 0$, $Q = W\ (\neq 0)$
  - E.g. Eat Q >0, walk/breathe W>0, $\Delta U = 0$



19.11 Every day, your body (a thermodynamic system) goes through a cyclic thermodynamic process like this one. Heat Q is added by metabolizing food, and your body does work W in breathing, walking, and other activities. If you return to the same state at the end of the day, $Q = W$ and the net change in your internal energy is zero.

Vocab

- Isolated System: Q in =0 , W = 0 (no interaction, no heat and no work)

  $\Delta U = 0$, U1 = U2

  e.g. free expansion

- Problem Solving Tip

  U final is the state. It is the same, no matter what path was taken.

15.2 Example

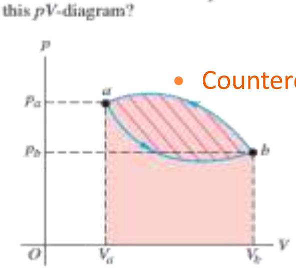
- **Example 19.3** **A cyclic process**

  Figure 19.12 shows a pV-diagram for a *cyclic* process in which the initial and final states of some thermodynamic system are the same. As shown, the state of the system starts at point a and proceeds counterclockwise in the pV-diagram to point b, then back to a; the total work is $W = -500$ J. (a) Why is the work negative? (b) Find the change in internal energy and the heat added during this process.

- Where is the -500 J in the picture?

19.12 The net work done by the system in the process aba is -500 J. What would it have been if the process had proceeded clockwise in this pV-diagram?

- Clockwise: W >0 (System does work)
- Counterclockwise: W<0 (work was done on system)



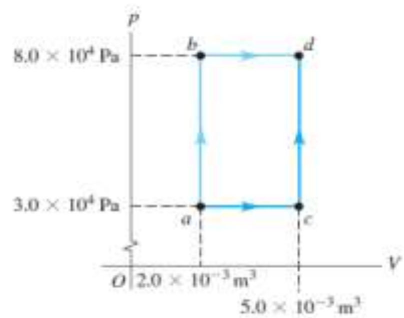
EXECUTE: (a) The work done in any step equals the area under the curve in the pV-diagram, with the area taken as positive if $V_2 > V_1$

15.2 Example

Example 19.4 **Comparing thermodynamic processes**

The pV-diagram of Fig. 19.13 shows a series of thermodynamic processes. In process ab, 150 J of heat is added to the system; in process bd, 600 J of heat is added. Find (a) the internal energy change in process ab; (b) the internal energy change in process abd (shown in light blue); and (c) the total heat added in process acd (shown in dark blue).

19.13 A pV-diagram showing the various thermodynamic processes.



15.2 Example (Isobaric)

Example 19.5 **Thermodynamics of boiling water**

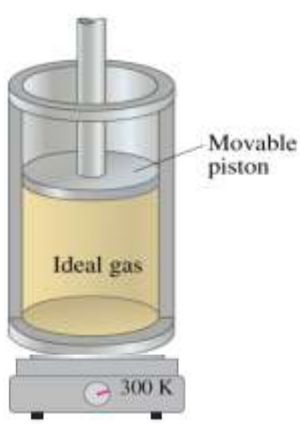
One gram of water ($1\ cm^3$) becomes $1671\ cm^3$ of steam when boiled at a constant pressure of 1 atm (1.013×10^5 Pa). The heat of vaporization at this pressure is $L_v = 2.256 \times 10^6$ J/kg. Compute (a) the work done by the water when it vaporizes and (b) its increase in internal energy.

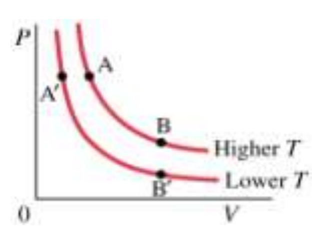
15.2 Example

Test Your Understanding of Section 19.4 Rank the following thermodynamic processes according to the change in internal energy in each process, from most positive to most negative. (i) As you do 250 J of work on a system, it transfers 250 J of heat to its surroundings; (ii) as you do 250 J of work on a system, it absorbs 250 J of heat from its surroundings; (iii) as a system does 250 J of work on you, it transfers 250 J of heat to its surroundings; (iv) as a system does 250 J of work on you, it absorbs 250 J of heat from its surroundings.

15.2 Kinds of Thermodynamic Processes

- Isothermal (T = constant, $\Delta U = 0$)
  - U = 3/2 nRT (ideal gas)
  - Qin → W to expand piston
  - Heat up slowly (heat reservoir)





15.2 Kinds of Thermodynamic Processes

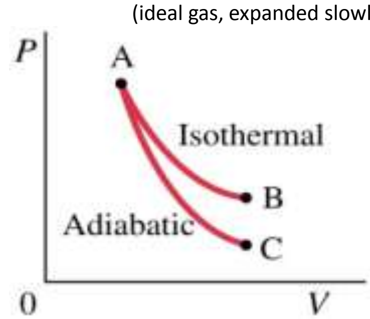
- Adiabatic (Q = 0)
  - Isolated or expands/compresses so fast there's not time for heat transfer
  - Examples:
    - Wine bottle
    - sonic boom cloud
    - Diesel engine's rapid compression*15,
    T↑ ignite without spark plugs.

19.14 When the cork is popped on a bottle of champagne, the pressurized gases inside the bottle expand rapidly and do work on the outside air ($W > 0$). There is no time for the gases to exchange heat with their surroundings, so the expansion is adiabatic ($Q = 0$). Hence the internal energy of the expanding gases decreases ($\Delta U = -W < 0$) and their temperature drops. This makes water vapor condense and form a miniature cloud.

15.2 Kinds of Thermodynamic Processes

- Adiabatic (Q = 0)
  - Isolated or expands/compresses so fast there's not time for heat transfer
  - Expand: W>0, ΔU < 0
    - Particles do work in expanding
    - Temperature and U decrease.
      - See how the curve switches an isotherm
      - Condensation
  - Compress: W<0, ΔU > 0
    - Add energy into system,
    all becomes internal energy
    - T ↑
  - Examples:
    - Wine bottle
    - sonic boom cloud
    - Diesel engine's rapid compression*15,
    T↑ ignite without spark plugs.

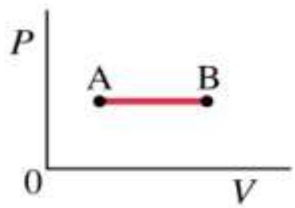
(ideal gas, expanded slowly)



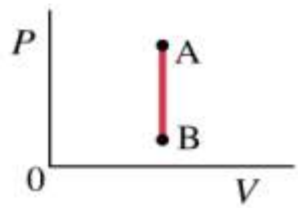
15.2 Kinds of Thermodynamic Processes

- Isobaric (P = constant)
  - W = P ΔV
  - ΔU = Qin – W
  - Example: Cooking at atmospheric pressure
- Isovolumetric, Isochoric (V = constant)
  - W = 0
  - ΔU = Qin
  - All heat goes into faster molecules

19.15 Most cooking involves isobaric processes. That's because the air pressure above a saucepan or frying pan, or inside a microwave oven, remains essentially constant while the food is being heated.



(a) Isobaric



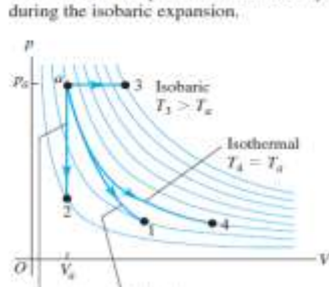
(b) Isovolumetric

15.2 Kinds of Thermodynamic Processes

TABLE 15–1 Simple Thermodynamic Processes and the First Law

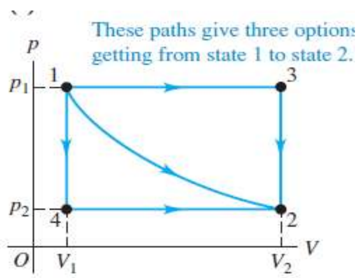
Process	What is constant:	The first law, $\Delta U = Q - W$, predicts:
Isothermal	T = constant	$\Delta T = 0$ makes $\Delta U = 0$, so $Q = W$
Isobaric	P = constant	$Q = \Delta U + W = \Delta U + P\,\Delta V$
Isovolumetric	V = constant	$\Delta V = 0$ makes $W = 0$, so $Q = \Delta U$
Adiabatic	$Q = 0$	$\Delta U = -W$

19.16 Four different processes for a constant amount of an ideal gas, all starting at state a. For the adiabatic process, $Q = 0$; for the isochoric process, $W = 0$; and for the isothermal process, $\Delta U = 0$. The temperature increases only during the isobaric expansion.



15.2 Kinds of Thermodynamic Processes

Test Your Understanding of Section 19.5 Which of the processes in Fig. 19.7 are isochoric? Which are isobaric? Is it possible to tell if any of the processes are isothermal or adiabatic?



15.2 Kinds of Thermodynamic Processes

- Example 5
- Engine 0.25 mol of monatomic ideal gas
- Rapid expansion (adiabatic) against piston
- T goes from 1150K to 400K
- How much work did the gas do?

15.2 Kinds of Thermodynamic Processes

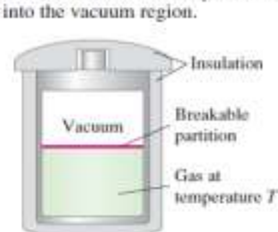
- Example 5
- Engine 0.25 mol of monatomic ideal gas
- Rapid expansion (adiabatic) against piston
- T goes from 1150K to 400K
- How much work did the gas do?

- W = Qin – ΔU = 0 - ΔU
  = 3/2 nR Δ T (P. 392 N* 3/2 R/N_A Δ T)
  = 3/2 * ¼ * 8.314(J/molK) * 750K
  = 2300 J

15.2 Internal energy of an Ideal Gas

- Ideal Gas
  - U depends on temperature only, not on P or V
  - U = 3/2 nRT

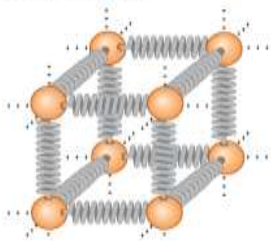
19.17 The partition is broken (or removed) to start the free expansion of gas into the vacuum region.



- Free expansion
  - ΔU = 0 (Q = 0 isolated. W = 0 walls don't move)
  - true for any gas, ideal or not
  - Ideal: U = constant, T = constant
  - Nonideal: U = constant, T≠constant. (distance↑, U = PE ↑ + KE↓, T↓)

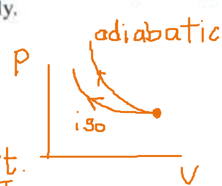
Test Your Understanding of Section 19.6 Is the internal energy of a solid likely to be independent of its volume, as is the case for an ideal gas? Explain your reasoning. (*Hint:* See Fig. 18.20.)

18.20 To visualize the forces between neighboring atoms in a crystal, envision every atom as being attached to its neighbors by springs.



Test Your Understanding of Section 19.8 You have four samples of ideal gas, each of which contains the same number of moles of gas and has the same initial temperature, volume, and pressure. You compress each sample to one-half of its initial volume. Rank the four samples in order from highest to lowest value of the final pressure. (i) a monatomic gas compressed isothermally; (ii) a monatomic gas compressed adiabatically; (iii) a diatomic gas compressed isothermally; (iv) a diatomic gas compressed adiabatically.

Test Your Understanding of Section 19.8 You have four samples of ideal gas, each of which contains the same number of moles of gas and has the same initial temperature, volume, and pressure. You compress each sample to one-half of its initial volume. Rank the four samples in order from highest to lowest value of the final pressure. (i) a monatomic gas compressed isothermally; (ii) a monatomic gas compressed adiabatically; (iii) a diatomic gas compressed isothermally; (iv) a diatomic gas compressed adiabatically.



- ii> iv > i= iii

$PV = \text{const.}$
nRT

$Q=0$

$W = \Delta U, \sim \frac{1}{2} m v^2$

dia↑ v↓ P↓

15-3 Human Metabolism

- metabolism = energy-transforming processes in an organism
- $\Delta U = Q - W$

(food) = (lose heat) – (walking)

- Example:

How many Calories should a 65 kg person eat for the energy used in a day of:

sleeping 8.0 hours

walking 1.0 h

light activity 4.0 h

sitting 11.0 h

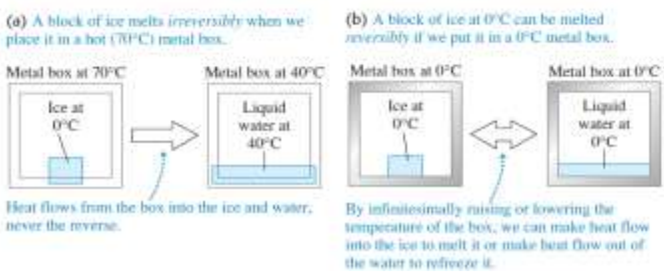
TABLE 15–2 Metabolic Rates (65-kg human)

Activity	Metabolic Rate (approximate) kcal/h	watts
Sleeping	60	70
Sitting upright	100	115
Light activity (eating, dressing, household chores)	200	230
Moderate work (tennis, walking)	400	460
Running (15 km/h)	1000	1150
Bicycling (race)	1100	1270

2ND LAW OF THERMODYNAMICS

- High to Low temperature flow. Preferred direction.
- Entropy increases naturally.
- 100% efficiency in heat engine is impossible.

- Irreversible process (naturally)
  - Car brakes
  - ΔT
  - Free expansion
- Reversible ~ near equilibrium



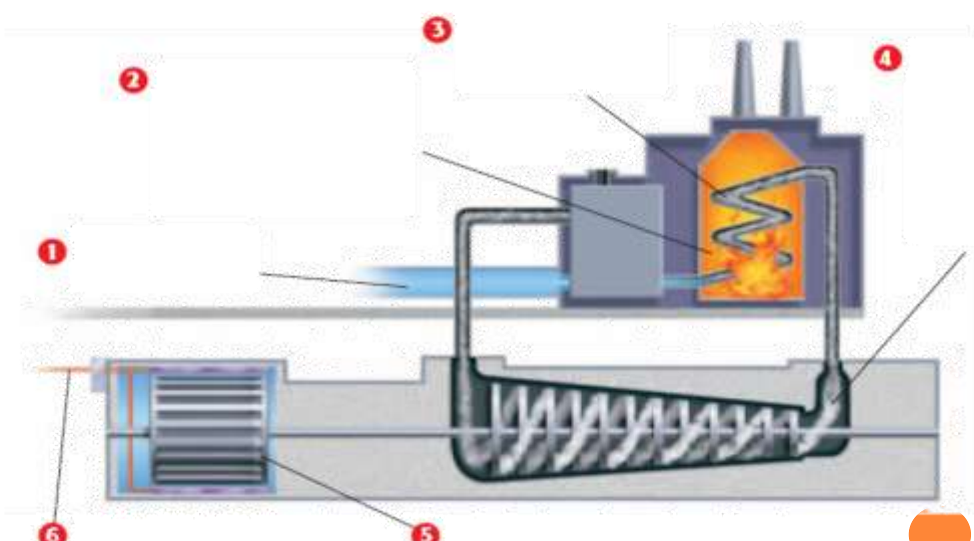
20.1 Reversible and irreversible processes.

Test Your Understanding of Section 20.1 Your left and right hands are normally at the same temperature, just like the metal box and ice in Fig. 20.1b. Is rubbing your hands together to warm them (i) a reversible process or (ii) an irreversible process?

Heat Engine

20.2 All motorized vehicles other than purely electric vehicles use heat engines for propulsion. (Hybrid vehicles use their internal-combustion engine to help charge the batteries for the electric motor.)

Heat Engine



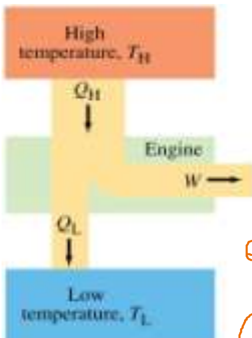
15-5 Heat Engine

- Device that changes thermal energy to mechanical work
- Basis of modern technology. Car, turbines in generator.
- Only when high to low temperature
- Must have $Q_L \neq 0$. Efficiency < 100%
- Cyclic process (or near it)

Steam engine
Hot reservoir (boiler)
Q_H = from flame and hot gas in the boiler

Working substance = steam

Cold reservoir = cold water and air to condense/cool steam.
(lake)



$\Delta U = 0$

$Q - W = 0$

$Q_H - Q_L = W$

$Q_H = Q_L + W$

$$e = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

car e~35%

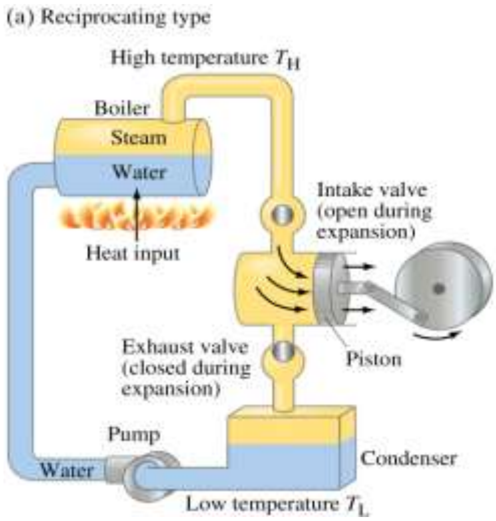
$(Q, W > 0)$

Want big ΔT
T_C limited by lake
T_H by boiler vapor pressure, i.e. boiler strength.
modern day: 235 atm, 500°C

20.16 To maximize efficiency, the temperatures inside a jet engine are made as high as possible. Exotic ceramic materials are used that can withstand temperatures in excess of 1000°C without melting or becoming soft.

20.12 The temperature of the firebox of a steam engine is much higher than the temperature of water in the boiler, so heat flows irreversibly from firebox to water. Carnot's quest to understand the efficiency of steam engines led him to the idea that an ideal engine would involve only *reversible* processes.

STEAM ENGINE



Expansion:
- intake valve open, exhaust valve closed
- High pressure gas does work on piston
- (like Carnot steps 4, 1)

Compression:
- intake valve closed, exhaust valve open
- piston does work on low pressure gas
- (like Carnot steps 2,3)

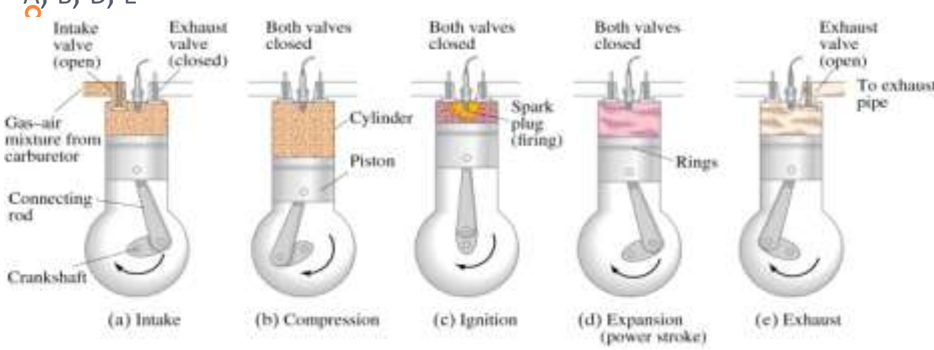
Why ΔT needed

$$\underset{\text{(high pressure)}}{W_{\text{Gas on piston}}} > \underset{\text{(low pressure)}}{W_{\text{piston on gas}}}$$

Can Replace wheel with turbine blades

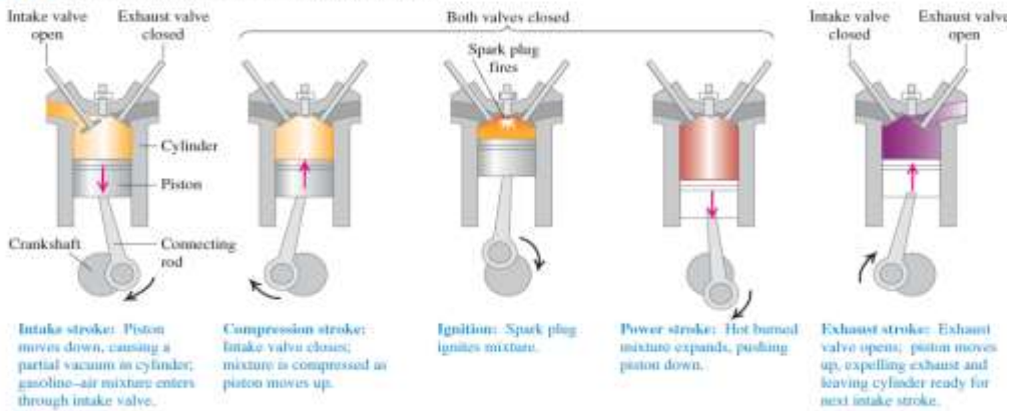
FOUR-STROKE INTERNAL COMBUSTION ENGINE

A, B, D, E



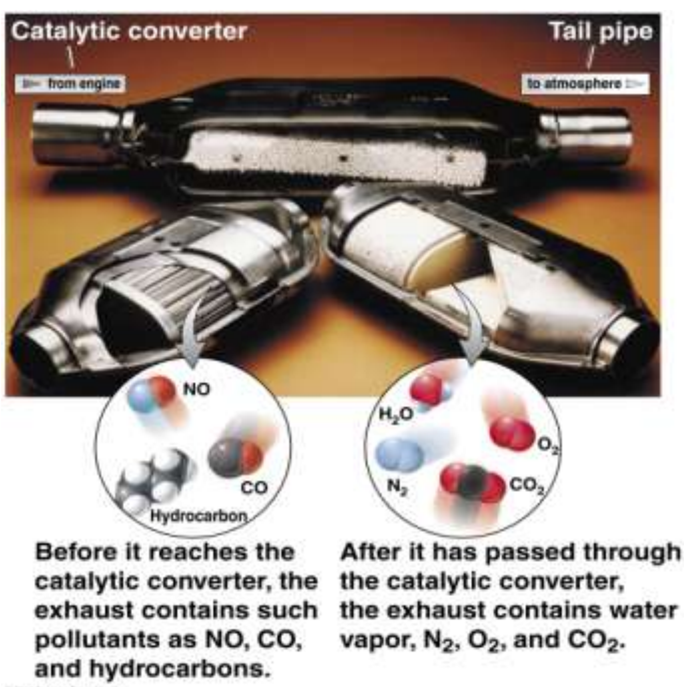
- a) intake
- b/c) compression/ignition.
- Usually by 8~10 volume ratio. Adiabatically
- V↓ P↑ T↑
- compress x15 → explodes spontaneously (instead of burning evenly by the spark)
  - makes knocking sound, bad for engine "Pre-ignition, detonation"
  - gasoline octane rating is the compression ratio
  - premium high-octane gasoline 10~13 for anti-knock qualities

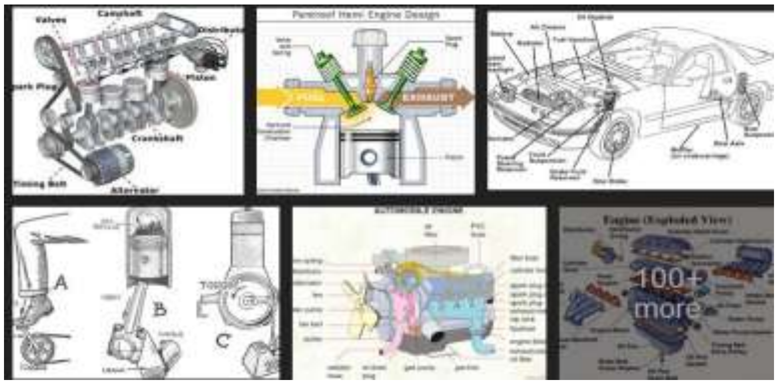
20.5 Cycle of a four-stroke internal-combustion engine.



•If there were just enough gas for complete combustion to H_2O and CO_2, the ignition would be unreliable.

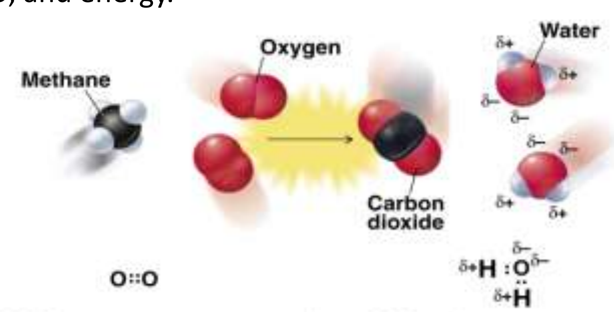
•A richer gas mixture is needed.
•The resulting incomplete combustion gives CO and pollution
•catalytic converter. Palladium, platinum, rhodium metals speed up rate of converting NO to N_2 and O_2 and unburned hydrocarbons to H_2O and CO





Human metabolism like combustion

- combustion oxidation-reduction reactions occur in the body. Simplified view: substitute food molecule for the methane., Food gives electrons to the oxygen inhaled and becomes CO, H2O, and energy.



(a) Reactant oxygen atoms share electrons equally in O_2 molecules.

(b) Product oxygen atoms pull electrons away from H atoms in H_2O molecules and are reduced.

EXAMPLE 15-8

- Auto efficiency 20%
- Produces average of 23 kJ work per second
- A) Heat input required?
- B) waste heat per second?

Example 20.1 **Analyzing a heat engine**

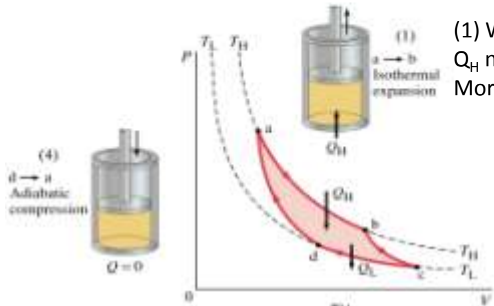
A gasoline truck engine takes in 10,000 J of heat and delivers 2000 J of mechanical work per cycle. The heat is obtained by burning gasoline with heat of combustion $L_c = 5.0 \times 10^4$ J/g. (a) What is the thermal efficiency of this engine? (b) How much heat is discarded in each cycle? (c) If the engine goes through 25 cycles per second, what is its power output in watts? In horsepower? (d) How much gasoline is burned in each cycle? (e) How much gasoline is burned per second? Per hour?

Test Your Understanding of Section 20.2 Rank the following heat engines in order from highest to lowest thermal efficiency. (i) an engine that in one cycle absorbs 5000 J of heat and rejects 4500 J of heat; (ii) an engine that in one cycle absorbs 25,000 J of heat and does 2000 J of work; (iii) an engine that in one cycle does 400 J of work and rejects 2800 J of heat.

Carnot Cycle: Use Kelvins!

- Hypothetical, idealized heat engine
- Max efficiency under 2nd Law, given the 2 heat reservoirs at T_H and T_C
- Rationale: work→ heat is irreversible
  - Try partial reversal as efficiently as possible
  - Avoid all irreversible processes
  - Heat flow through finite temperature drop is irreversible
    - Isothermal T_H, T_C (compression/expansion)
    - When T changes, make Q = 0 (adiabatic)

Carnot Cycle: Use Kelvins!

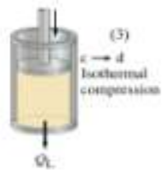


(1) Work done on piston.
Q_H needed to maintain internal U, T
More T, more Q_H needed

<u>ΔT needed</u>

$Q_H \sim T_H$

(3) $\Delta U = 0 \rightarrow W = Q_L$
= 0 iff



- molecules are "not moving"
- 0 Kelvins (impossible)
- So $Q_L \neq 0$, $e \neq 100\%$

T_H =constant → $\Delta U = 0 \rightarrow W = Q_H$

$Q_H = W_{\text{Gas on piston}}$

= area under PV curve (P =nRT/V)

$$= \int_{V_a}^{V_b} \frac{nRT_H}{V} dV = nRT_H \ln\left(\frac{V_B}{V_A}\right)\ldots$$

$$e = \frac{W}{Q_H} = 1 - \frac{Q_C}{Q_H} = 1 - \frac{T_C}{T_H}$$

- Actually, at molecular level at 0K,
- there's a minimum of KE + PE
- Due to quantum effects, KE is not really 0
- T< 10^{-7} K has been achieved so far in labs

Carnot Cycle: Use Kelvins!

- done slowly as series of equilibrium states (and reversible)
- Practically: turbulence, friction, quickly done. Irreversible.

$$e = \frac{W}{Q_H} = 1 - \frac{Q_C}{Q_H} = 1 - \frac{T_C}{T_H}$$

- Max efficiency possible in a heat engine with the two temperatures given.
- Carnot is reversible. Real engines are irreversible.
- Well-designed heat engines can reach 60~80% of the Carnot efficiency.

EXAMPLE 9 STEAM ENGINE EFFICIENCY

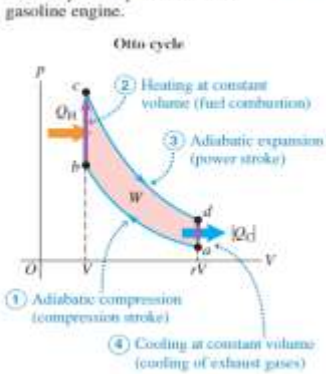
- A steam engine operates between 500^{o}C and 270^{o}C.
- What is the max possible efficiency of this engine?

- Example 10 A Phony claim?
- Heat input per second: 9.0 kJ at 435 K
- Heat output per second: 4.0 KJ at 285 K
- Really?

OTTO CYCLE (IDEALIZED GASOLINE COMBUSTION ENGINE)

Test Your Understanding of Section 20.3 For an Otto-cycle engine with cylinders of a fixed size and a fixed compression ratio, which of the following aspects of the pV-diagram in Fig. 20.6 would change if you doubled the amount of fuel burned per cycle? (There may be more than one correct answer.) (i) the vertical distance between points b and c; (ii) the vertical distance between points a and d; (iii) the horizontal distance between points b and a.

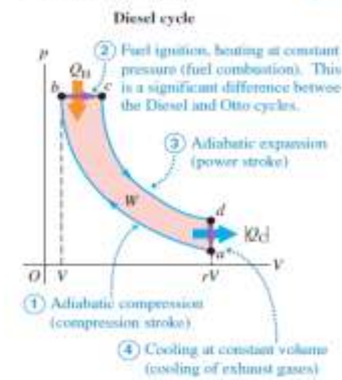
20.6 The pV-diagram for the Otto cycle, an idealized model of the thermodynamic processes in a gasoline engine.



Diesel Cycle (Also a Gasoline Combustion Engine)

- Diesel engine is similar to gasoline engine.
- The only difference is there's no fuel in the cylinder during most of the compression. Fuel is injected at end of compression and beginning of power stroke, just fast enough to keep Pressure constant.
- No fuel during compression means less chance at pre-ignition. Very efficient, but high maintenance.

20.7 The pV-diagram for the idealized Diesel cycle.



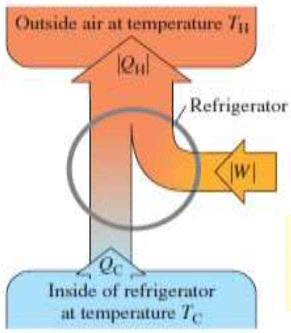
15.6 Refrigerators, Air conditioners, Heat Pumps

- heat engine: hot to cold flow → work done
- Fridge, AC
  - Work done → push cold to hot
- heat pump
  - work done → pump heat from cold outside to warm inside

15.6 Refrigerator, Air conditioner

- Absorb energy from inside fridge/room and release it outside.

20.8 Schematic energy-flow diagram of a refrigerator.

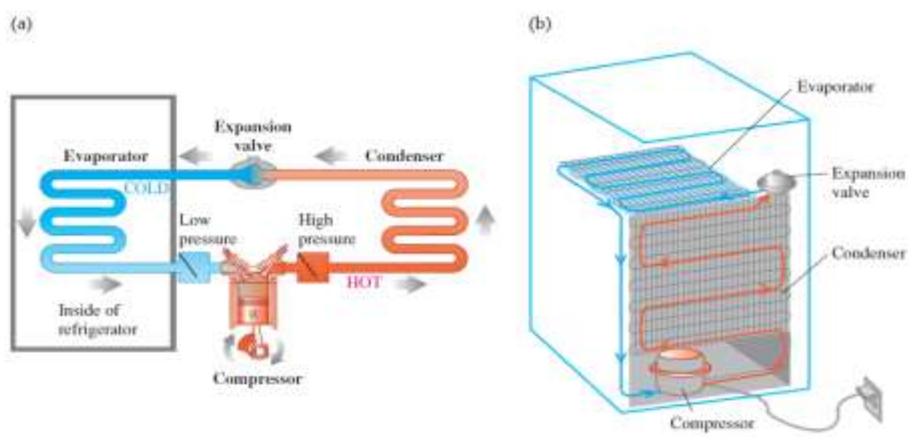


$$K = \frac{|Q_C|}{|W|} = \frac{|Q_C|}{|Q_H| - |Q_C|} \quad \text{(coefficient of performance of a refrigerator)}$$

$$\mathrm{COP}_{\mathrm{ideal}} = \frac{T_L}{T_H - T_L}, \qquad \left[\begin{array}{l}\text{refrigerator and} \\ \text{air conditioner}\end{array}\right] \qquad (15\text{-}6c)$$

15.6 Refrigerator

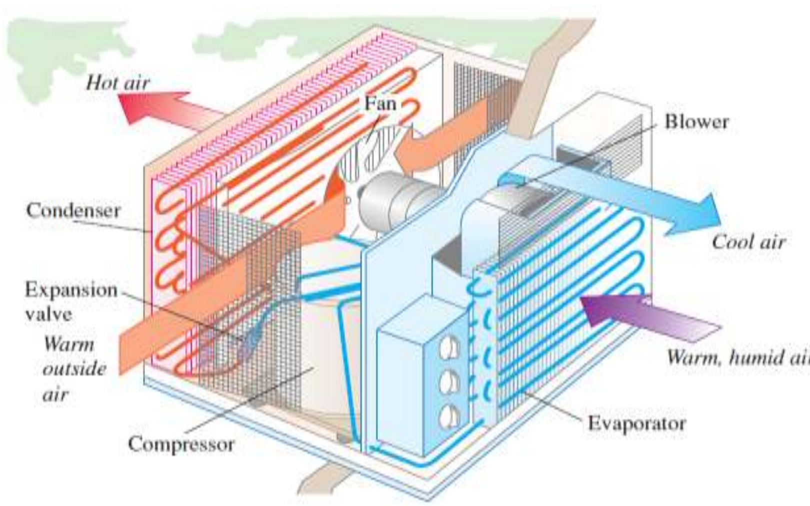
20.9 (a) Principle of the mechanical refrigeration cycle. (b) How the key elements are arranged in a practical refrigerator.

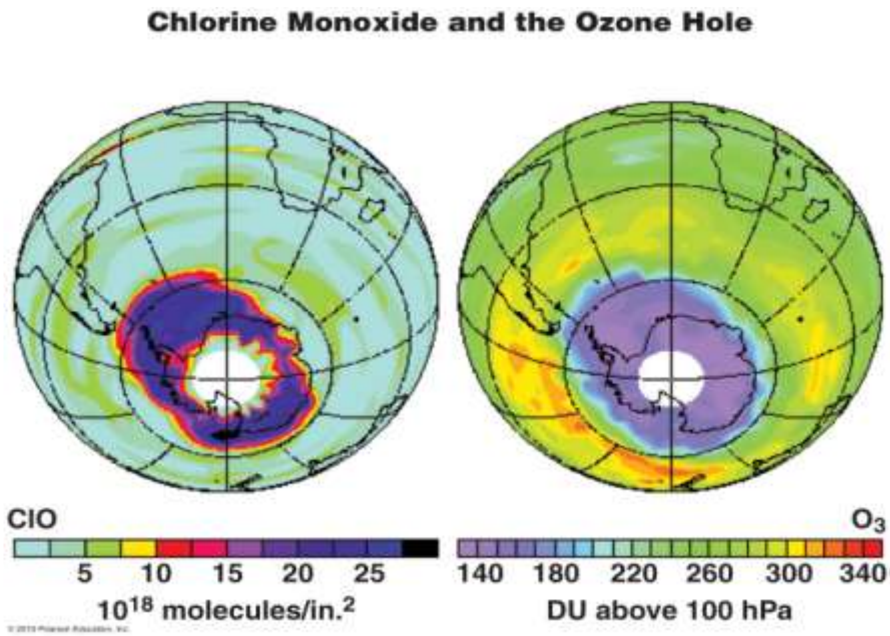


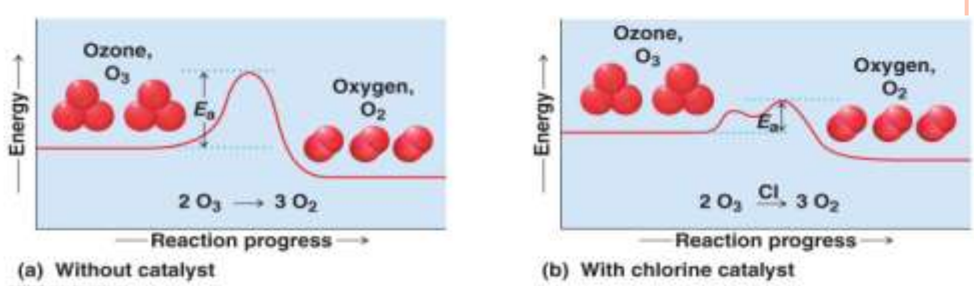
15.6 Refrigerator

- compressor: adiabatic. V↓ P↑ T↑ fluid → gas,
- outside: hot gas gives heat off to environment. partially becomes liquid
- Expansion valve controls rate of adiabatic expansion V ↑ P ↓ T ↓ gas → fluid
- Inside: cold fluid absorbs heat from food, cooling them and partially vaporizing.
- The fluid then enters the compressor to begin another cycle. The compressor, usually driven by an electric motor requires energy input and does work on the working substance during each cycle.

15.6 Refrigerator, Air conditioner



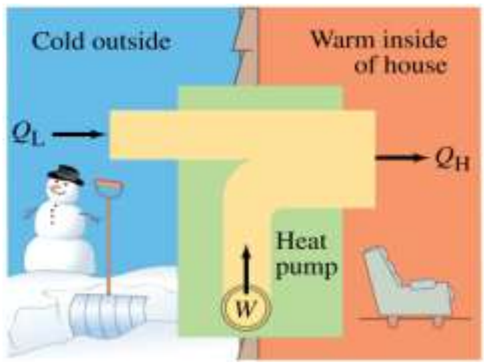

Chlorine Monoxide and the Ozone Hole
ClO
5 10 15 20 25
10^{18} molecules/in.^{2}
O_3
140 180 220 260 300 340
DU above 100 hPa


Ozone, O_3
Oxygen, O_2
E_a
Energy
$2\,O_3 \longrightarrow 3\,O_2$
Reaction progress
(a) Without catalyst
Ozone, O_3
Oxygen, O_2
E_a
Energy
$2\,O_3 \xrightarrow{Cl} 3\,O_2$
Reaction progress
(b) With chlorine catalyst

15-6 Heat Pumps

A heat pump can heat a house in the winter:

$$\text{COP} = \frac{Q_H}{W}. \quad \text{[heat pump]} \quad (15\text{-}7)$$



15.6 Fridge, AC, Heater

- Example 11
  - freezer K = 2.8 uses 200Watts power
  - How long to freeze ice cube of 600g water at 0°C?
  - L_F = 333 kJ/kg
- Example 12: Heat pump has K = 3.0 and is rated to do work at 1500 W
  - a) How much heat can it add to a room per second?
  - b) Turn it around into an AC. K same?
  - c) 1500 W of power for 4500 W heat. Are we getting something for nothing?
- Example 12 had 3000 W of heat extracted from the room. In example 11, how much heat is extracted from the fridge?

15.6

Example 20.2 **Analyzing a Carnot engine I**

A Carnot engine takes 2000 J of heat from a reservoir at 500 K, does some work, and discards some heat to a reservoir at 350 K. How much work does it do, how much heat is discarded, and what is its efficiency?

Example 20.4 **Analyzing a Carnot refrigerator**

If the cycle described in Example 20.3 is run backward as a refrigerator, what is its coefficient of performance?

SEER RATING

$$\text{SEER} = \frac{\text{heat removed in Btu (1 Btu} = 1056\ \text{J)}}{\text{electrical input in watt-hours}}$$

Test Your Understanding of Section 20.4 Can you cool your house by leaving the refrigerator door open?

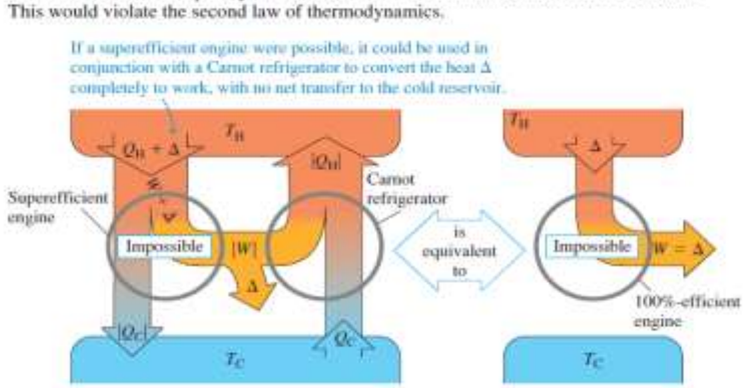
2ND LAW OF THERMODYNAMICS

- High to Low temperature flow. Preferred direction.
- Entropy increases naturally.
- 100% efficiency in heat engine is impossible.
- cold to hot flow needs work

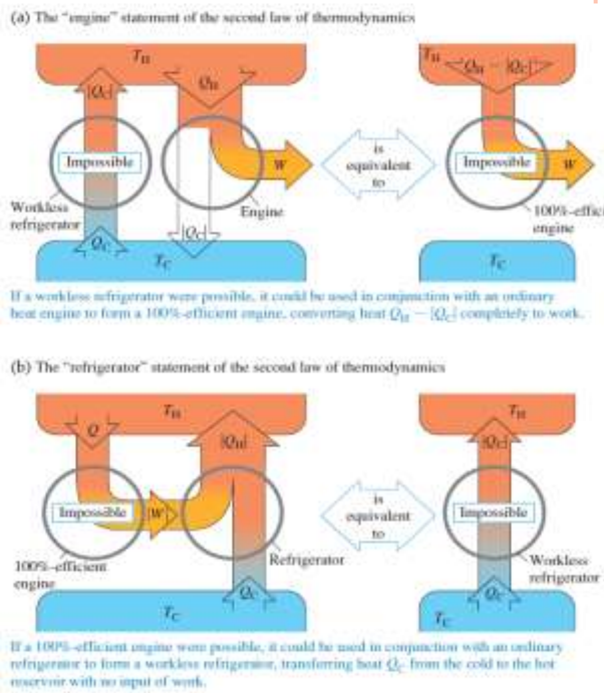
2ND LAW OF THERMODYNAMICS

- High to Low temperature flow. Preferred direction.
- Entropy increases naturally.
- **100% efficiency in heat engine is impossible.)Kevin-Planck "Engine" statement)**

20.15 Proving that the Carnot engine has the highest possible efficiency. A "superefficient" engine (more efficient than a Carnot engine) combined with a Carnot refrigerator could convert heat completely into work with no net heat transfer to the cold reservoir. This would violate the second law of thermodynamics.



- 100% efficiency in heat engine is impossible. ⇔
- **cold to hot flow needs work (*Clausius statement.)***



Test Your Understanding of Section 20.5 Would a 100%-efficient engine (Fig. 20.11a) violate the *first* law of thermodynamics? What about a workless refrigerator (Fig. 20.11b)?

2^{ND} LAW OF THERMODYNAMICS

- **High to Low temperature flow. Preferred direction.**
- **Entropy increases naturally.**
- 100% efficiency in heat engine is impossible.
- cold to hot flow needs work

- Entropy = measure of disorder of system
  depends on state (like P, V, n, T, U) unlike heat, work

- Change in entropy
  $Q>0$ absorb heat, entropy$\uparrow$
  $Q<0$ absorb heat, entropy$\downarrow$

$$\Delta S = \frac{Q}{T}, \qquad (15\text{-}8)$$

15.7~15.9

- **High to Low temperature flow. Preferred direction.**
- **Entropy increases naturally.**

$$\Delta S = \frac{Q}{T}, \qquad (15\text{-}8)$$

- Entropy of an isolated system can never decrease. It can only stay the same (for idealized only) or increase (all natural processes).

$$\Delta S_{system} + \Delta S_{environment} \geq 0$$

15.7~15.9

- **Entropy increases naturally.**

$$\Delta S_{system} + \Delta S_{environment} \geq 0$$

$\downarrow \qquad\qquad \uparrow\uparrow$

animal takes food → cell (very ordered)

a great deal of waste is produced (disordered)

Application Entropy Changes in a Living Organism

When a kitten or other growing animal eats, it takes ordered chemical energy from the food and uses it to make new cells that are even more highly ordered. This process alone lowers entropy. But most of the energy in the food is either excreted in the animal's feces or used to generate heat, processes that lead to a large increase in entropy. So while the entropy of the animal alone decreases, the *total* entropy of animal plus food *increases*.

Entropy

- Example 13: ice cube 56 grams at 0°C
- half melts to 0°C water
- change in entropy?

- Example 14: Temperature changes – use computer, calculus, or average
- 50.0 kg water at 20.00°C is mixed with
- 50.0kg water at 24.00°C
- Change in entropy?

15-10 Entropy and Statistics

- microstate
  - x(t), v(t) of each and every particle
  - no computer can keep track of all molecules in a room
- macrostate
  - P, V, n, T, U, S

- 1 macrostate can have many possible microstates
  (event) (equally likely samples)

Entropy

Macrostate	Possible Microstates (H = heads, T = tails)	Number of Microstates
4 heads	H H H H	1
3 heads, 1 tail	H H H T, H H T H, H T H H, T H H H	4
2 heads, 2 tails	H H T T, H T H T, T H H T, H T T H, T H T H, T T H H	6
1 head, 3 tails	T T T H, T T H T, T H T T, H T T T	4
4 tails	T T T T	1

- What is the probability that there will be at least 2 heads?

Entropy and Statistics

- More coins/gas particles, order is less likely
- Entropy increases is equivalent to saying that disorder is the most probable event.

TABLE 15–3 Probabilities of Various Macrostates for 100 Coin Tosses

Macrostate: Heads	Macrostate: Tails	Number of Microstates	Probability
100	0	1	7.9×10^{-31}
99	1	1.0×10^{2}	7.9×10^{-29}
90	10	1.7×10^{13}	1.4×10^{-17}
80	20	5.4×10^{20}	4.2×10^{-10}
60	40	1.4×10^{28}	0.011
55	45	6.1×10^{28}	0.047
50	50	1.0×10^{29}	0.077
45	55	6.1×10^{28}	0.047
40	60	1.4×10^{28}	0.011
20	80	5.4×10^{20}	4.2×10^{-10}
10	90	1.7×10^{13}	1.4×10^{-17}
1	99	1.0×10^{2}	7.9×10^{-29}
0	100	1	7.9×10^{-31}

Thermal Pollution, Global Warming, Energy Resources

- Thermal Pollution:
  - CO_2 traps too much infrared
  - hot lakes make O_2 less for fish. ecosystems
  - solar panels contribute to surface warming
  - windmills don't look nice, bird hazard may affect weather.
- ozone depletion with refrigerants
- Resources:
  - fossil fuels (nonrenewable)
  - Nuclear energy (nonrenewable)

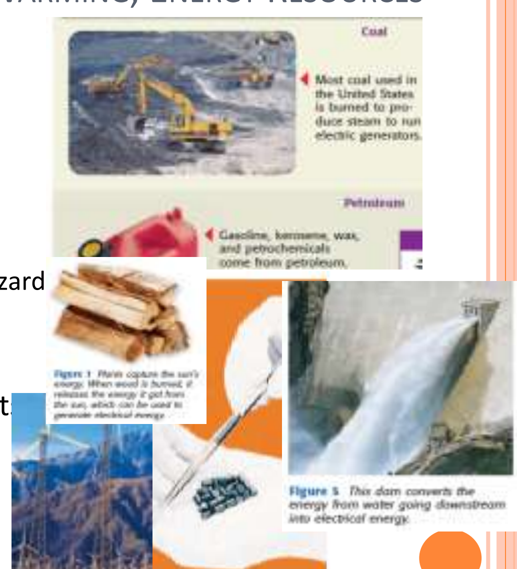


Figure 4 A single uranium fuel pellet contains the energy equivalent of about 1 metric ton of coal.

Table 1 Advantages and Disadvantages of Energy Resources		
Energy Resource	**Advantages**	**Disadvantages**
Fossil fuels	• provide a large amount of thermal energy per unit of mass • are easy to get and transport • can be used to generate electricity and to make products such as plastic	• are nonrenewable • produce smog • release substances that can cause acid precipitation • create a risk of oil spills
Nuclear	• is a very concentrated form of energy • does not produce air pollution	• produces radioactive waste • is nonrenewable
Solar	• is an almost limitless source of energy • does not produce pollution	• is expensive to use for large-scale energy production • is practical only in sunny areas
Water	• is renewable • does not produce air pollution	• requires dams, which disrupt a river's ecosystem • is available only where there are rivers
Wind	• is renewable • is relatively inexpensive to generate • does not produce air pollution	• is practical only in windy areas
Geothermal	• is an almost limitless source of energy • power plants require little land	• is practical only in areas near hot spots • produces wastewater, which can damage soil
Biomass	• is renewable • is inexpensive	• requires large areas of farmland • produces smoke