COMMACK HIGH SCHOOL

INTERNATIONAL BACCALAUREATE
STANDARD LEVEL PHYSICS

2019

Topic 3: Thermal Physics
Option B2 Thermodynamics

NAME ______________________________

TEACHER ____________________________

https://ibphysics2016.wikispaces.com/Topic+3+%28Core%29Topic

3: Thermal physics
3.1 – Thermal concepts

Essential idea: Thermal physics deftly demonstrates the links between the macroscopic measurements essential to many scientific models with the microscopic properties that underlie these models.

Nature of science: Evidence through experimentation: Scientists from the 17th and 18th centuries were working without the knowledge of atomic structure and sometimes developed theories that were later found to be incorrect, such as phlogiston and perpetual motion capabilities. Our current understanding relies on statistical mechanics providing a basis for our use and understanding of energy transfer in science.

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Topic 3: Thermal physics
3.1 – Thermal concepts

Understandings:
- Molecular theory of solids, liquids and gases
- Temperature and absolute temperature
- Internal energy
- Specific heat capacity
- Phase change
- Specific latent heat

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Topic 3: Thermal physics
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Applications and skills:
- Describing temperature change in terms of internal energy
- Using Kelvin and Celsius temperature scales and converting between them
- Applying the calorimetric techniques of specific heat capacity or specific latent heat experimentally
- Describing phase change in terms of molecular behaviour
- Sketching and interpreting phase change graphs
- Calculating energy changes involving specific heat capacity and specific latent heat of fusion and vaporization

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Guidance:
- Internal energy is taken to be the total intermolecular potential energy + the total random kinetic energy of the molecules
- Phase change graphs may have axes of temperature versus time or temperature versus energy
- The effects of cooling should be understood qualitatively but cooling correction calculations are not required

Data booklet reference:
- $Q = mc\Delta T$
- $Q = mL$

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International-mindedness:
- The topic of thermal physics is a good example of the use of international systems of measurement that allow scientists to collaborate effectively

Theory of knowledge:
- Observation through sense perception plays a key role in making measurements. Does sense perception play different roles in different areas of knowledge?

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Utilization:
- Pressure gauges, barometers and manometers are a good way to present aspects of this sub-topic
- Higher level students, especially those studying option B, can be shown links to thermodynamics (see *Physics* topic *9* and option sub-topic *B.4*)
- Particulate nature of matter (see *Chemistry* sub-topic *1.3*) and measuring energy changes (see *Chemistry* sub-topic *5.1*)
- Water (see *Biology* sub-topic *2.2*)

Topic 3: Thermal physics
3.1 – Thermal concepts

Aims:
- **Aim 3:** an understanding of thermal concepts is a fundamental aspect of many areas of science
- **Aim 6:** experiments could include (but are not limited to): transfer of energy due to temperature difference; calorimetric investigations; energy involved in phase changes

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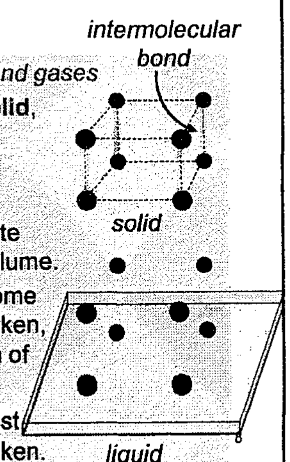
Molecular theory of solids, liquids and gases
- The three phases of matter are **solid**, **liquid**, and **gas**.
- In a solid the molecules can only vibrate. They cannot translate.
- In a liquid the molecules can vibrate and move about freely in a fixed volume.
- In going from a solid to a liquid, some of the intermolecular bonds are broken, giving the molecules more freedom of motion.
- In going from a liquid to a gas, most of the intermolecular bonds are broken.



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Phase change

- The process of going from a solid to a liquid is called **melting**.
- The process of going from a liquid to a gas is called **boiling**.
- Each process can be reversed.

PHASE CHANGE	*PROCESS*	*EXAMPLE*
solid → liquid	melting	ice to water
liquid → solid	freezing	water to ice
liquid → gas	boiling	water to steam
gas → liquid	condensing	steam to droplets
solid → gas	sublimation	frost evaporation
gas → solid	deposition	frost

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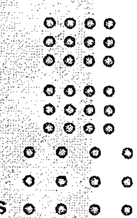
Internal energy

- All substances are composed of individual molecules that are in vibration.
- As we heat up a substance its vibrations become more energetic. This is an increase in the kinetic energy of the molecules.
- Simultaneously, as heat energy is being added the molecules are also moving farther apart. This is an increase in the potential energy of the substance.
- The two energies together are called the **internal energy** of the substance. Thus $E_{INT} = E_K + E_P$.
- When thermal energy (heat) is added to a substance it is stored as internal energy.



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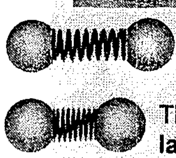
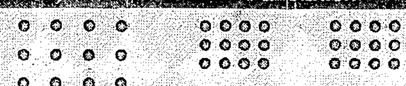
Internal energy

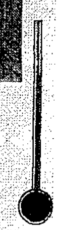
$E_{INT} = E_K + E_P$. total internal energy

Total Internal Energy

Potential Energy (due to inter-molecular forces)	***Kinetic Energy*** (due to vibration and translation)







Think of Hooke's law $F = -kx$ **and phase change**

The thermometer measures internal kinetic energy

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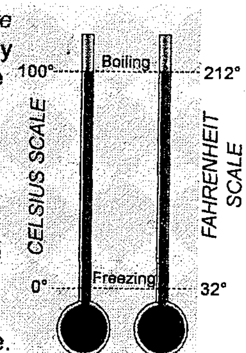
Temperature and absolute temperature

- Because absorption of thermal energy (heat) causes materials to expand, the fluid in a thermometer can be used to indirectly measure temperature.
- Since water is a readily-available substance that can be frozen, and boiled within a narrow range of temperatures, many thermometers are calibrated using these temperatures.
- We will be using the **Celsius scale** in physics because it is a simpler scale.
- Temperature only reveals the internal kinetic energy.
- E x p a n s i o n reveals internal potential energy.



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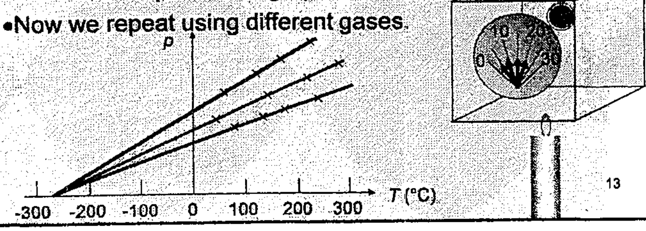
Temperature and absolute temperature

- When gas is heated in an enclosed space its pressure p increases.
- The following experiment plots pressure p vs. temperature T in Celsius.
- We can extrapolate the graph.
- Now we repeat using different gases.



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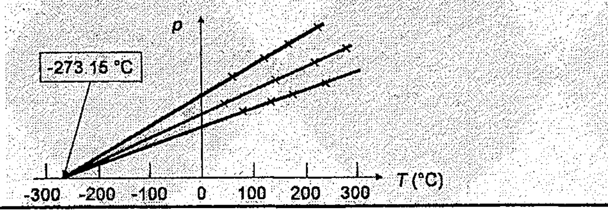
Temperature and absolute temperature

- The lowest pressure p that can exist is zero.
- Surprisingly, the temperature at which *any* gas attains a pressure of zero is the same, regardless of the gas.
- The Celsius temperature at which the pressure is zero (for all gases) is -273 °C.



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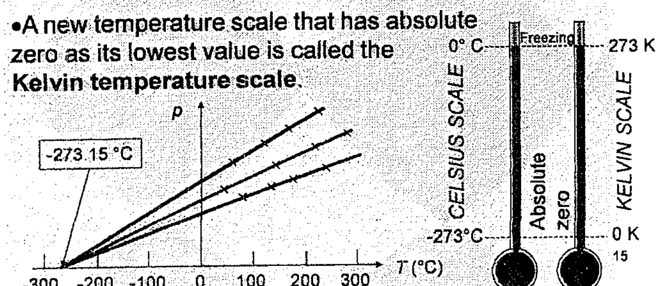
Temperature and absolute temperature

- Because the lowest pressure that can exist is zero, this temperature is the lowest temperature that can exist, and it is called **absolute zero**.
- A new temperature scale that has absolute zero as its lowest value is called the **Kelvin temperature scale**.



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Converting between Kelvin and Celsius temperatures

- The simple relationship between the Kelvin and Celsius scales is given here:

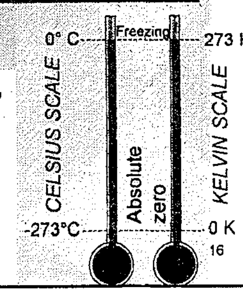
$T(K) = T(°C) + 273$ **Kelvin and Celsius relationship**

FYI • Note that there is no degree symbol on Kelvin temperatures.

EXAMPLE: Convert 100 °C to Kelvin, and 100 K to C°.

SOLUTION:

- $T(K) = T(°C) + 273$
  $T = 100 + 273 = 373$ K.
- $100 = T(°C) + 273$
  $T = -173$ °C.



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Specific heat capacity

•Traditionally in the U.S., heat energy is measured in calories or kilocalories.

One kilocalorie is *the amount of heat needed to raise the temperature of one kilogram of water by exactly 1 C°.*	definition of the kilo-calorie

•1 calorie is needed to raise the temperature of 1 gram (instead of a kilogram) of water 1 C°.

•In Europe they don't talk about "low calorie cola."

•Instead, they talk about "low Joule cola."

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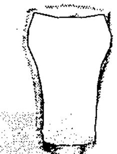
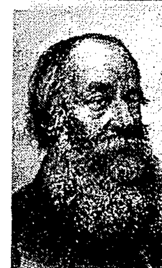
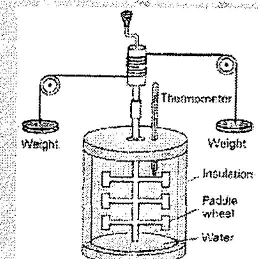


Specific heat capacity

•Obviously there must be a conversion between Joules (J) and kilocalories (kcal).

1 kcal = 4.186 kJ	mechanical equivalent of heat





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Specific heat capacity

EXAMPLE: How many joules is 450000 calories?

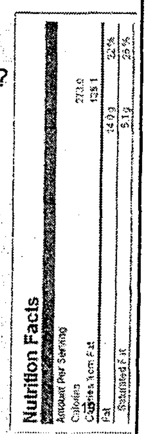
SOLUTION: Use 1 kcal = 4.186 kJ:

450000 cal = (450 ~~kcal~~)(4.186 kJ / 1 ~~kcal~~)

= 1900 kJ.

PRACTICE: A Snickers™ bar has 273.0 Cal. For foods, Calories are really kcal. How many joules are in a Snickers™ bar?

•273.0 Cal = (273.0 ~~kcal~~)(4.186 kJ / 1 ~~kcal~~)
= 1143 kJ = 1,143,000 J!



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Specific heat capacity

•Different materials absorb heat energy in different ways.

•This means that if we have two different substances having the same mass m, and each absorbs the same amount of heat Q, their increase in temperature ΔT may be different.

•We define the specific heat capacity c of a substance as the amount of heat needed per unit temperature increase per unit mass.

$Q = mc\Delta T$	specific heat capacity c defined

•Each material has its own unique value for c.

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Specific heat capacity

•Here are some specific heats for various materials.

Specific Heats c of Various Substances at 20°C and 1 atm		
Substance	J / kg·C°	kcal/kg·C° (or cal/g·C°)
Air (at 50°C)	1050	0.25
Water (at 15°C)	4186	1.00
Steam (at 110°C)	2010	0.48
Ice (at -5°C)	2100	0.50
Wood	1680	0.40
Ethyl Alcohol	2430	0.58
Steel	460	0.11

FYI

•Note that specific heat units for c are $(J\ kg^{-1}\ C^{\circ -1})$.

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Calculating energies involving specific heat capacity

$Q = mc\Delta T$	specific heat capacity c defined

EXAMPLE: Air has a density of about $\rho = 1.2\ kg\ m^{-3}$. How much heat, in joules, is needed to raise the temperature of the air in a 3.0 m by 4.0 m by 5.0 m room by 5°C?

SOLUTION:

•From the previous table we see that $c = 1050$.

•The change in temperature is given: $\Delta T = 5°C$.

•We get the mass from $\rho = m / V$ or

$$m = \rho V = (1.2)(3)(4)(5) = 72\ kg.$$

•$Q = mc\Delta T = (72)(1050)(5) = 378000$ J or 380 kJ.

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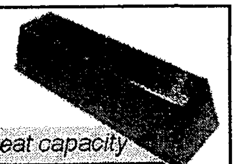


Calculating energies involving specific heat capacity

$Q = mc\Delta T$	specific heat capacity c defined

PRACTICE: Suppose we have a 200.-kg steel ingot and a 200.-kg block of wood, both at room temperature (20.0°C). If we add 1,143,000 J of heat (the energy of a Snickers™ bar) to each object, what will its final temperature be?

SOLUTION:

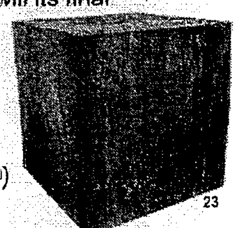
•For both, $Q = mc\Delta T = mc(T - T_0)$.

•Steel: $1143000 = 200(460)(T - 20)$

$12.4 = T - 20$ or $T = 32.4°C$.

•Wood: $1143000 = 200(1680)(T - 20)$

$3.40 = T - 20$ or $T = 23.4°C$.



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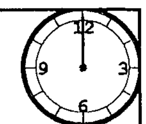
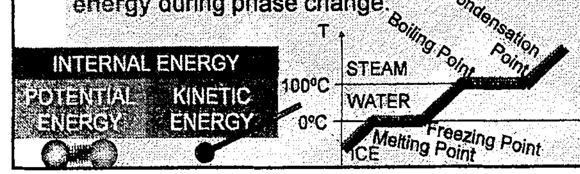
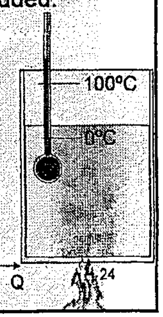


Sketching and interpreting phase change graphs

•Suppose a thermometer is frozen in ice, and the ice is further cooled to a temperature of -20°C. We slowly add heat, and plot the temperature vs. the heat Q added:

•Since the thermometer measures kinetic energy, and since the temperature doesn't change during the phase change, the heat must be getting stored **ONLY** as potential energy during phase change.





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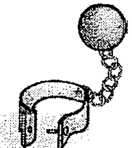


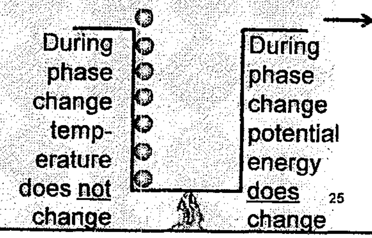
Phase change in terms of molecular behavior

•As a model to help explain phase change consider a molecule in an open box which can move left and right but must remain "captured" in the box.

•As more heat is stored as potential energy, the particle in our model gains height.

•Finally, the potential energy is great enough to break the intermolecular bonds and change the phase of the substance.

•The molecule is free!



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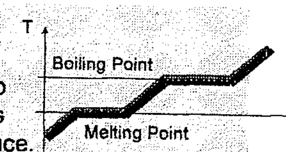
Specific latent heat

•*Latent heat* means *hidden heat*, by which we mean that there is no temperature indication that heat is being lost or gained by a substance.



•The **specific latent heat** L is defined in this formula:

$Q = mL$	specific latent heat L defined

•Note that since there is no temperature change during a phase change, there is no ΔT in our formula. The units for L are (J kg^{-1}).

FYI

•Use $Q = mL$ during phase change (when $\Delta T = 0$).

•Use $Q = mc\Delta T$ otherwise (when $\Delta T \neq 0$).

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Specific latent heat

•Since there are two phase changes (two plateaus), each substance has two latent heats.

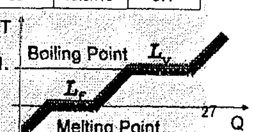
Latent Heats Lof Various Substances at 1 atm

Substance	Melting Point °C	L_f J/kg	L_f kcal/kg	Boiling Point °C	L_v J/kg	L_v kcal/kg
Water	0	3.33×10^5	80	100	22.6×10^5	540
Mercury	-39	0.12×10^5	2.8	357	2.7×10^5	65
Oxygen	-219	0.14×10^5	3.3	-183	2.1×10^5	51
Gold	1063	0.65×10^5	15.4	2660	15.8×10^5	377

•L_f is the **latent heat of fusion**.

•L_v is the **latent heat of vaporization**.

•The temperatures associated with the phase changes are also given.



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Specific latent heat

EXAMPLE: Compare boiling and evaporation.

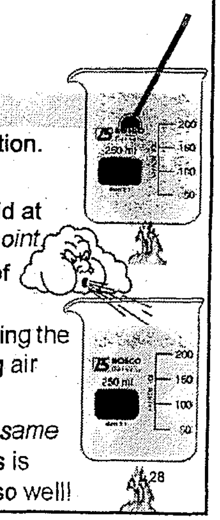
SOLUTION:

•**Boiling** takes place within the whole liquid at the <u>same</u> temperature, called the *boiling point*.

•**Evaporation** occurs only at the surface of a liquid and can occur at <u>any</u> temperature.

•Evaporation can be enhanced by increasing the surface area, warming the liquid, or having air movement at the surface.

•*Boiling and evaporation both remove the same amount of heat energy from the liquid.* This is why sweating removes excess body heat so well!



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Calculating energies involving specific latent heat

$Q = mL$	specific latent heat L defined

EXAMPLE:

Bob has designed a 525-kg ice chair. How much heat must he remove from water at 0°C to make the ice chair (also at 0°C)?

SOLUTION:

- In a phase change $\Delta T = 0$ so we use $Q = mL$.
- Since the phase change is freezing, we use L_f.
- For the water-to-ice phase change $L_f = 3.33\times10^5$ J kg^{-1}.
- Thus $Q = mL = (525)(3.33\times10^5) = 175\times10^6$ J.
- Bob can now chill in his new chair.

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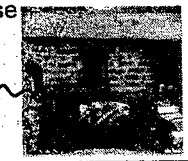
*Conduction, convection and **thermal radiation***

- Thermal energy can be transferred from a warmer mass to a cooler mass by three means: conduction, convection, and radiation.
- This energy transfer is called **heating** and **cooling**.
- Only **thermal radiation** transfers heat without any physical medium such as solid, liquid or gas.

EXAMPLE: The heat from a wood-burning stove can be felt from all the way across the room because photons carrying infrared energy can travel through empty space. When these photons strike you, they are absorbed as heat. This process of thermal energy transfer is called **thermal radiation**. *See Topic 8.2.*



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***Conduction**, convection and thermal radiation*

- When two solids of different temperatures touch, thermal energy is transferred from the hotter object to the cooler object through a process called **conduction**.
- When atoms of one portion of a material are in contact with vibrating atoms of another portion, the vibration is transferred from atom to atom.

Direction of heat flow

- High T portions vibrate more than low T portions, so we can imagine the vibration "impulse" to travel through the material, from high T to low T.

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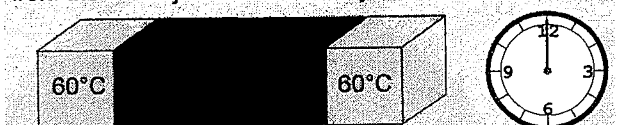
***Conduction**, convection and thermal radiation*

- Consider a material that acts as a conductor of heat from the hot object to the cold object.



Direction of heat flow

- During the process the hot object loses energy and cools, while the cold object gains energy and warms.
- At the end of the process the two ends have reached **thermal equilibrium** at which point there is no more net transfer of heat.

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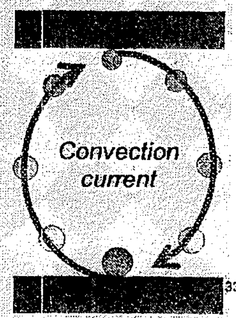
*Conduction, **convection** and thermal radiation*

- Another form of heat transfer is called **convection**.
- Convection requires a fluid as a medium of heat transfer.
- For example, hot air is less dense than cold air, so it rises.
- But as it rises it cools, and so becomes denser and sinks.
- We thus obtain a cycle, which forms a circulation called a **convection current**.
- Convection currents drive many interesting physical systems as the next slides illustrate.



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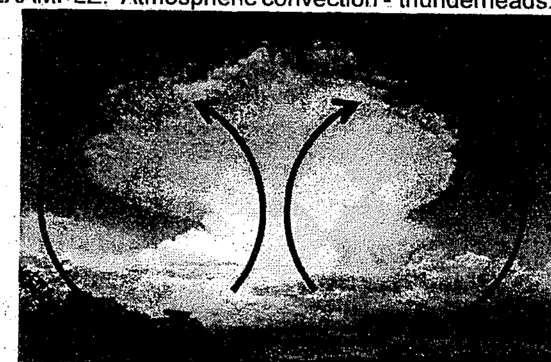
*Conduction, **convection** and thermal radiation*

EXAMPLE: Atmospheric convection - thunderheads.



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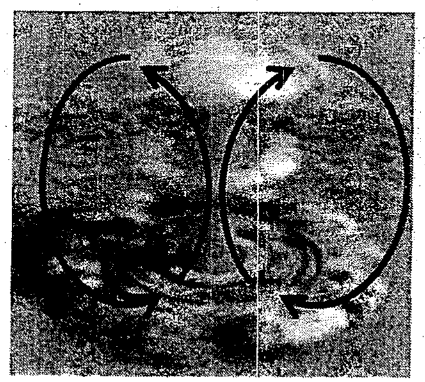
*Conduction, **convection** and thermal radiation*

EXAMPLE: Atmospheric convection - nuclear detonation.



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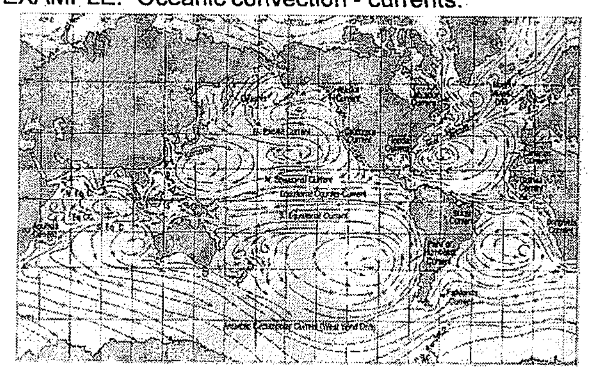
*Conduction, **convection** and thermal radiation*

EXAMPLE: Oceanic convection - currents.



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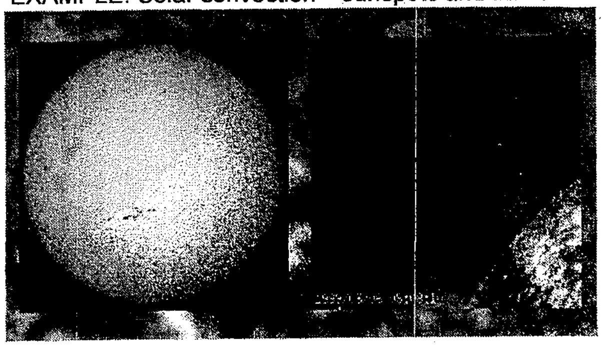
Conduction, ***convection*** *and thermal radiation*

EXAMPLE: Solar convection – sunspots and flares.



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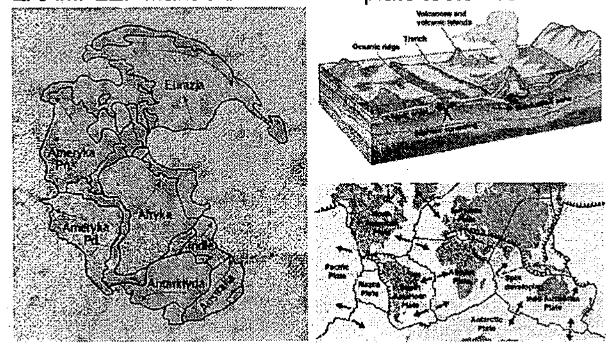
Conduction, ***convection*** *and thermal radiation*

EXAMPLE: Mantle convection – plate tectonics.



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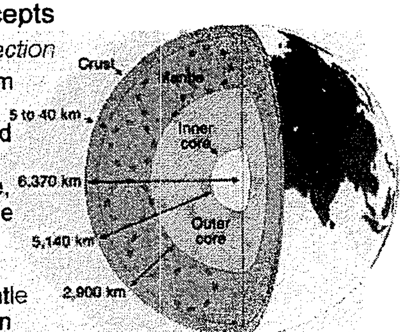
Topic 3: Thermal physics

3.1 – Thermal concepts

Plate tectonics - convection

- The residual heat from the formation of Earth, and the heat generated by radioactive decay deep within the mantle, combine to produce the perfect conditions for convection currents.
- Even though the mantle acts similar to a solid in many ways, it is really a special kind of fluid that would be liquid like lava if it weren't for the tremendous pressure it is under due to overlaying layers.



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Topic 3: Thermal physics

3.1 – Thermal concepts

Plate tectonics - convection

- Specific to the NGSS, and related to convection currents, we have **plate tectonics**, which is the study of crustal plate motion over the surface of Earth over time.
- It is these convection currents in the mantle that drive plate tectonics.

- **Spreading centers** are where plates separate.
- **Subduction zones** are where plates collide.

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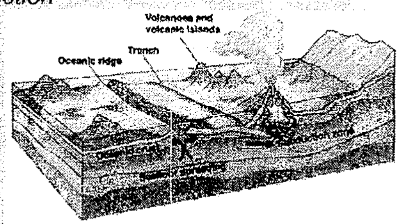
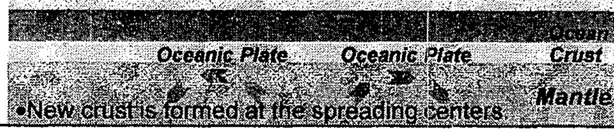
Topic 3: Thermal physics
3.1 – Thermal concepts

Plate tectonics - convection

- Spreading centers are usually located in the ocean and produce landforms called **oceanic ridges**.



- Oceanic ridges form because as the oceanic plates separate, magma can well up into the void.



- New crust is formed at the spreading centers

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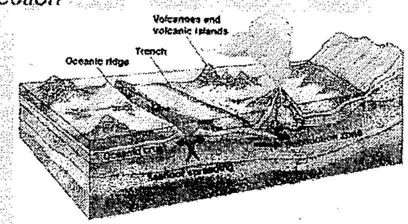
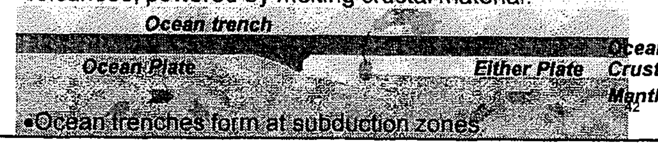
Topic 3: Thermal physics
3.1 – Thermal concepts

Plate tectonics - convection

- A true subduction zone is where one of two colliding plates is driven underneath the other.
- Mountains created by the buckling crust can form, as well as volcanoes, powered by melting crustal material.





- Ocean trenches form at subduction zones

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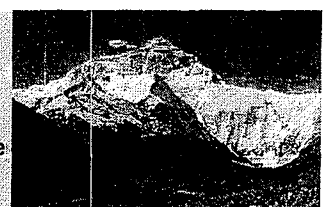
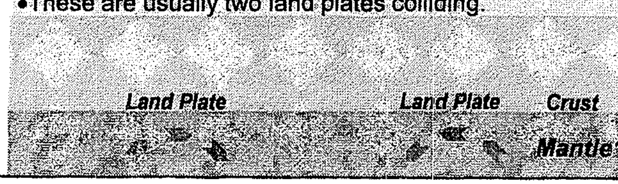
Topic 3: Thermal physics
3.1 – Thermal concepts

Plate tectonics - convection

- Generally when oceanic plates collide with land plates, the oceanic plate is the one that is driven underneath in the subduction zone.



- Plates can also collide and crumple, forming mountains without subduction.
- These are usually two land plates colliding.



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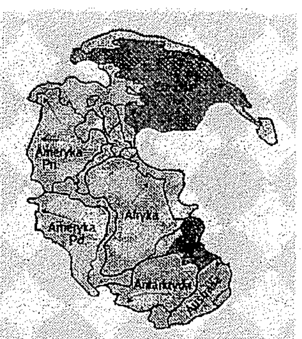
Topic 3: Thermal physics
3.1 – Thermal concepts

Plate tectonics

- **Pangaea** is the name given to the early landform that was more or less all the present-day continents placed close together.



- Because of continental drift (on the average of two inches per year), Pangaea has split up into the present-day continents, which are still in motion.
- In the following animation, note how the Indie plate collides with the Eurazja plate. What mountain range do you think this collision created?

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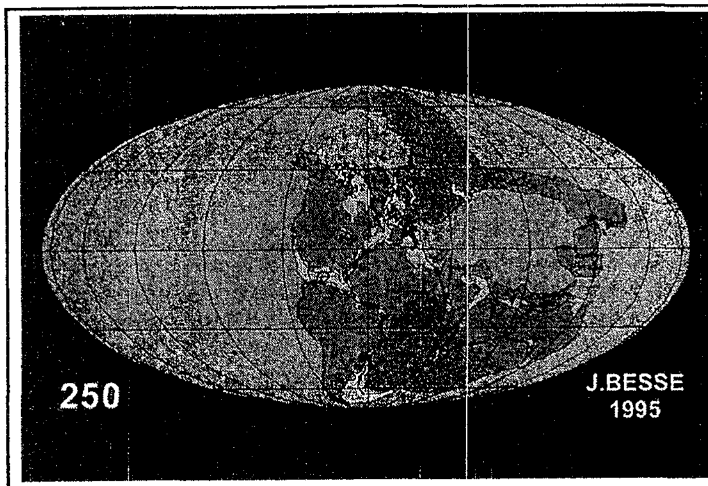
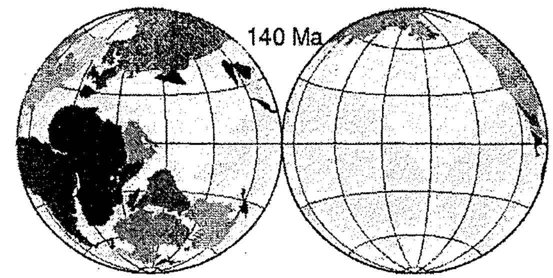


Credit: Jean Besse, Institut de Physique du Globe de Paris 45



Credit: Alex Copley, Ashley Kennard, Jessica Kim, and Lindsey Stancliff

PRACTICE: How do you think continental drift might affect the evolution of living species? 46

Topic 3.1 – Thermal concepts **Formative Assessment**

NAME: ________________________________ TEAM:__

THIS IS A PRACTICE ASSESSMENT. Show formulas, substitutions, answers (in spaces provided) and units!

The following questions are about internal energy.

1. What are the two forms of internal energy? 1. ____________________

2. Suppose a liquid's starting temperature is 35°C and its ending temperature is 20°C. Explain what happens to each form of internal energy.

   ____

3. What measuring device should you use to determine that the internal potential energy of a substance has changed? 3. ____________

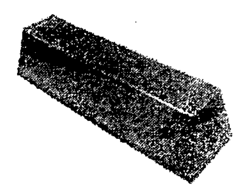
4. What measuring device should you use to determine that the internal kinetic energy of a substance has changed? 4. ____________

The following questions are about temperature scales.

5. Convert 83°C to Kelvin. 5. ____________

6. Convert 83 K to Celsius. 6. ____________

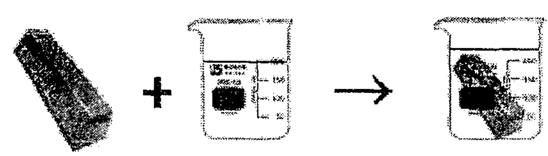
The specific heat capacity of a particular block of steel is 450 J kg^{-1} C°$^{-1}$. When we add 4.2×10^{6} J of thermal energy to a block of this steel its temperature increases by 12 °C.



7. What is the mass of the above block? 7. ____________

8. Suppose we now have 220-kg of this same kind of steel. How much heat must be added to raise its temperature by 12 °C? 8. ____________

The specific heat capacity of a particular steel is 450 J kg^{-1} C°$^{-1}$. The specific heat of water is 4186 J kg^{-1} C°$^{-1}$. The mass of the steel is 520 grams. The mass of the water is 350 grams. The container is extremely light plastic and acts as a good insulator (it doesn't absorb any of the heat). The steel is heated up to 95°C and placed in the water, which is originally at a temperature of 15°C.



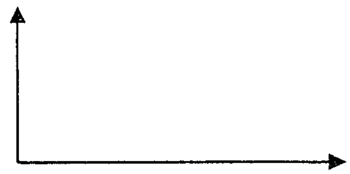
9. What is the final temperature of the combination, assuming no heat is lost to the container or the environment? 9. ____________

10. Which substance loses heat? 10. ____________

3.1-13

The following question is about phase change.

11. Draw a *T* vs. *Q* graph for a typical substance that shows its five characteristic regions. Label the melting point and the boiling point. Label the freezing point, and the condensation point.



The following questions are about changing the temperature and phase of a 0.75-kg piece of ice. Its starting temperature is -18°C.

12. The ice is warmed up to 0.0°C without melting. How much heat energy in Joules is needed? 12. ________________

13. The ice at 0°C is now warmed up until it all melts, becoming water at 0°C. How much heat energy in Joules is needed? 13. ________________

Specific Heats	
Substance	*J/kg·C°*
Water	4186
Steam	2010
Ice	2100

Latent Heats			
Melting Point C°	L_f *J/kg*	*Boiling Point C°*	L_v *J/kg*
0	3.33×10^5	100	22.6×10^5

14. The water at 0°C is now warmed up until it reaches a temperature of 100°C but does not begin to boil. How much heat energy in Joules is needed? 14. ________________

15. The water at 100°C is now warmed up until it all turns into steam at a temperature of 100°C. How much heat energy in Joules is needed? 15. ________________

16. The steam at 100°C is now warmed up until it reaches a temperature of 118°C. How much heat energy in Joules is needed? 16. ________________

17. 0.75 kilograms of ice at -18°C is warmed up to become steam at 118°C. How much heat energy in Joules is needed? 17. ________________

The following questions are about thermal energy transfer

18. What are the three processes by which thermal energy can be transferred from a warmer mass to a cooler mass? 1)________________ 2)________________ 3)________________

19. Describe the three processes you just listed. Which one is responsible for continental drift?
    1)____
    2)____
    3)____

20. In a well-written paragraph, describe and explain the process of plate tectonics, to include convection, the mantle, continental drift, Pangaea, evolution, oceanic plates, continental plates, spreading centers, oceanic ridges, subduction zones, ocean trenches, volcanoes, and mountain building.

3.1-14

TOPIC 3 THERMAL PHYSICS Name: ______________________

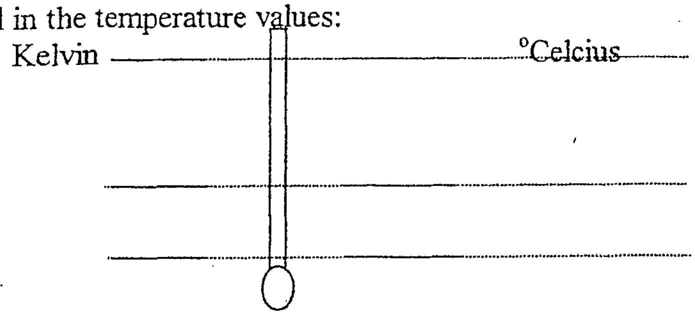
IB SL Physics DUE:

Please answer the following questions after doing the assigned reading in Giancoli and reading the handouts.

1. Define temperature based on the kinetic molecular theory.

2. Object A is in contact with object B. Object A is at 35°C and object B is at 42°C. What do you know about the heat energy transfer between A and B?

3. Fill in the temperature values:



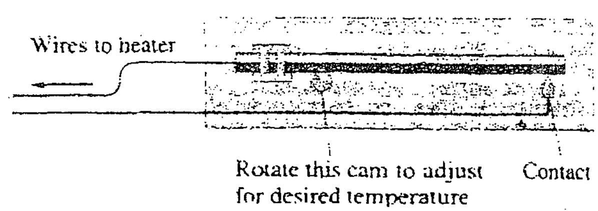
boiling point H_2O

freezing point H_2O

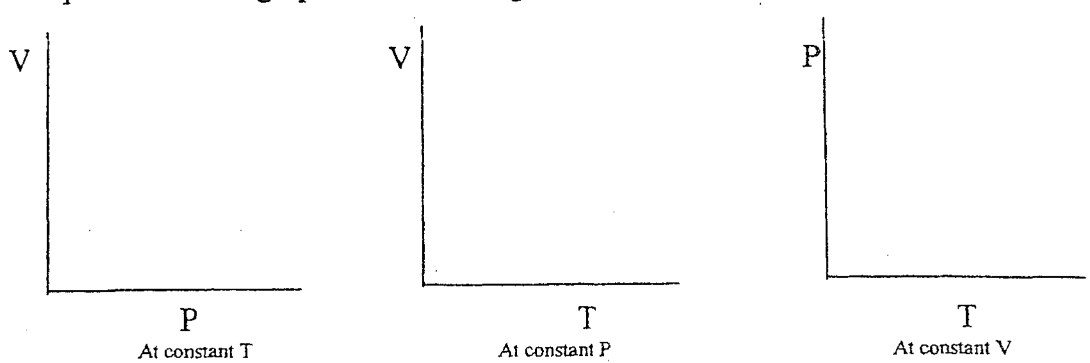
Absolute Zero

4. Give an example of two objects in thermal equilibrium.

5. Figure 13–24 shows a diagram of a typical *thermostat* used to control a furnace (or other heating or cooling system). The bimetallic strip consists of two strips of different metals bonded together. Explain why this strip bends when the temperature changes, and how this controls the furnace.



6. Complete the three graphs for an ideal gas:



7. Under what conditions will gases behave most closely like ideal gases?

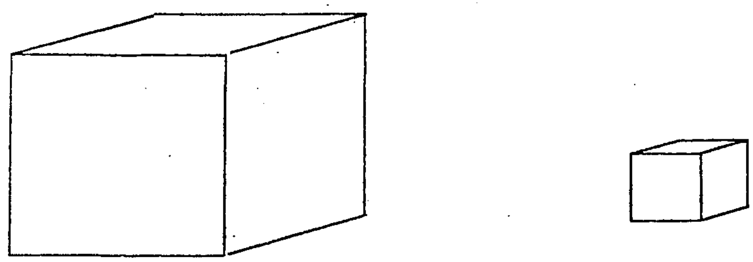
8. What are the following temperatures on the Kelvin scale?

a) 86°C b) 100°C c) 5500°C

9. If 3.00 m^3 of a gas initially at STP is placed under a pressure of 4.00 atm, the temperature of the gas rises to 38.0°C. What is the volume?

Note: STP stands for "standard temperature and pressure" T=273 K (0°C), P=1.00 atm.

10.



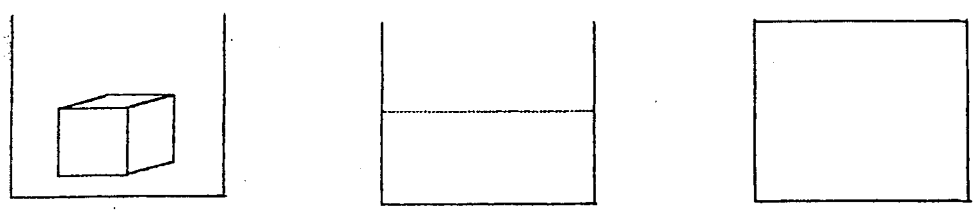
A: 1 Kg of substance X
T = 300 K

B: 1 gram of substance X
T = 300 K

a) Compare the average KE of the molecules of block A to the average KE of the molecules of block B. EXPLAIN.
b) Compare the internal energy (thermal energy) of block A to block B.
c) If block A is placed in contact with block B will heat transfer occur? EXPLAIN.

11. List and define the three methods of heat transfer.

12. Describe the orientation and motion of the particles that make up the three phases.



Solid Liquid Gas

13. Explain why burns caused by steam on the skin are often more severe than burns caused by water at 100°C.

14. Will potatoes cook faster if the water is boiling faster?

15. Why is the liner of a thermos bottle silvered, and why does it have a vacuum between its walls?

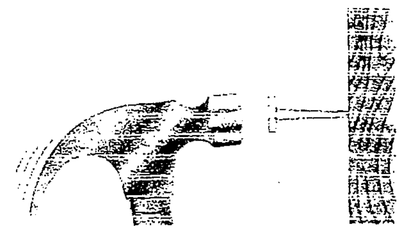
16. Why is the heat of vaporization of water larger than the heat of fusion of water?

(melting point)
Silver Mpt = 961°C

	Specific heat J/Kg°C	Heat of fusion J/Kg	Heat of vaporization J/Kg
IRON	450	-	-
SILVER	230	0.88×10^5	23×10^5
WATER (ice)	2100	3.33×10^5	22.6×10^5
WATER (liquid)	4186		
WATER (steam)	2010		

17. (I) What is the specific heat of a metal substance if 135 kJ of heat is needed to raise 5.1 kg of the metal from 20°C to 30°C?

18. (II) The 1.20-kg head of a hammer has a speed of 8.0 m/s just before it strikes a nail (Fig. 14–13) and is brought to rest. Estimate the temperature rise of a 14-g iron nail generated by ten such hammer blows done in quick succession. Assume the nail absorbs all the energy.



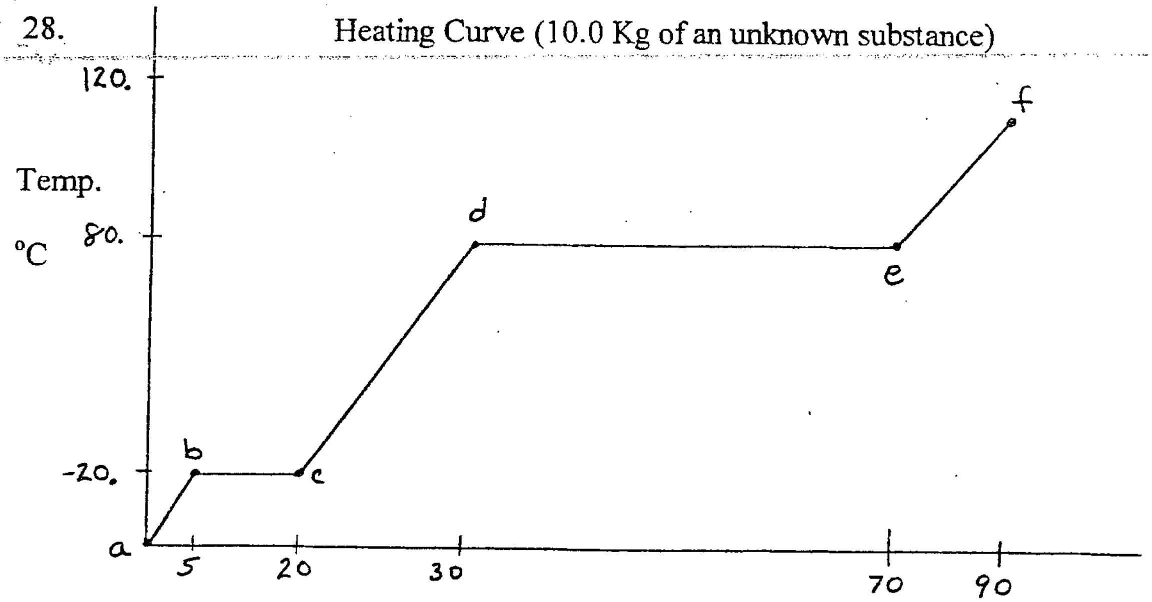
19. *(I) How much heat is needed to melt 16.50 kg of silver that is initially at 20°C?*

26. (II) An iron boiler of mass 230 kg contains 830 kg of water at 20°C. A heater supplies energy at the rate of 52,000 kJ/h. How long does it take for the water (*a*) to reach the boiling point, and (*b*) to all have changed to steam?

27. Heat energy is added to cause a solid to melt yet temperature is constant during the phase change.

a) EXPLAIN Why temperature does not change even though heat is added.
b) EXPLAIN the changes in molecular behavior when a solid becomes a liquid.

28. Heating Curve (10.0 Kg of an unknown substance)



Time (minutes)

Heat is added at a constant rate of 200. J/minute.

a) Calculate the heat of fusion of this unknown substance using the heating curve above.
b) Calculate the specific heat for the liquid phase of this unknown substance using the heating curve above.
c) Complete the chart below.

	a-b	b-c	c-d	d-e	e-f
List the phases	solid	solid + liquid			
Describe what is occurring		melting (solid to liquid)			
Temp. change? (yes/no)			yes		
Phase change? (yes/no)				yes	
ΔKE (inc/dec/RTS)		no, RTS			yes, INC.
ΔPE (inc/dec/RTS)				yes, INC	
Write the equation used in this section of the graph	$Q = mc\Delta T$				

Assignment Preview

Course: LS_IB_SL_12, section 1_2, 2003-2004

Dates:

Available: Wed Apr 14 2004 12:15 PM EST

Due: Thu Apr 15 2004 12:15 PM EST

Close this window

temperature, kinetic theory, and heat transfer #1

1. Giancoli5 13.P.028. [50658] What are the following temperatures on the Kelvin scale?

(a) 83°C

[356] K

(b) 72°F

[295] K

(c) -100°C

[173] K

(d) 5600°C

[5870] K

2. Giancoli5 13.P.031. [50659] If 2.00 m^3 of a gas initially at STP is placed under a pressure of 5.00 atm, the temperature of the gas rises to 31.0°C. What is the volume?

[0.445] m^3

3. Giancoli5 13.P.034. [50660] A storage tank at STP contains 15.5 kg of nitrogen (N_2).

(a) What is the volume of the tank?

[12.4] m^3

(b) What is the pressure if an additional 20.0 kg of nitrogen is added?

[2.32e+05] Pa

4. Giancoli5 13.P.038. [50661] If 40.0 L of oxygen at 13.0°C and an absolute pressure of 2.45 atm are compressed to 33.8 L and at the same time the temperature is raised to 50°C, what will the new pressure be?

[3.27] atm

5. Giancoli5 14.P.003. [7674] To what temperature will 7780 J of work raise 2.9 kg of water initially at 9.5°C?

[10.1]°C

6. Giancoli5 14.P.009. [7680] What is the specific heat of a metal substance if 126 kJ of heat is needed to raise 4.8 kg of the metal from 20°C to 30°C?

[2620] J/kg · C°

Submit for Testing

3.1-19

3\. 1. This question is about determining the specific latent heat of fusion of ice.

A student determines the specific latent heat of fusion of ice at home as follows. She takes some ice from the freezer, measures its mass and mixes it with a known mass of water in an insulating jug. She stirs until all the ice has melted and measures the final temperature of the mixture. She also measured the temperature in the freezer and the initial temperature of the water.

She records her measurements as follows:

Mass of ice used	m_i	0.12 kg
Initial temperature of ice	T_i	-12 °C
Initial mass of water	m_w	0.40 kg
Initial temperature of water	T_w	22 °C
Final temperature of mixture	T_f	15 °C

The heat capacities of water and ice are $c_w = 4.2\ \text{kJ kg}^{-1}\ °\text{C}^{-1}$ and $c_i = 2.1\ \text{kJ kg}^{-1}\ °\text{C}^{-1}$ respectively.

(a) Set up the appropriate equation, representing energy transfers during the process of coming to thermal equilibrium, that will enable them to solve for the specific latent heat L_i of ice. Insert values into the equation from the data above, **but do not solve the equation.** *[5]*

. . . .

. . . .

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3.1-20

(This question continues on the following page)

Worksheet Gas Laws

$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$

$K = C^{o} + 273$

1. A gas occupies 645 ml when the pressure measures 740 torrs. What will be its volume at 850 torrs?

2. If 50 liters of oxygen are measured at 24°C, what would be the volume at 8°C, assuming constant pressure?

3. A gas occupies 410 ml at 0°C and 760 torrs. What will its volume be at -10°C and 785 mm?

4. A gas has a volume of 632 ml at a temperature of 32°C. What will be its volume if the temperature is lowered to -42°C?

5. Nitrogen gas has a volume of 525 ml at 27°C. At 43°C and 740 torrs, it has a volume of 600 ml. What was its original pressure?

6. 900 ml of a gas are measured at 700 torrs pressure. At what pressure would it occupy 855 ml?

7. Hydrogen gas has a volume of 640 ml at 12°C. Its volume decreases to 510 ml. What is its new temperature?

8. The pressure of a gas is 740 torrs when its volume is 400 ml. Calculate the pressure of the gas if it is allowed to expend to 500 ml?

9. A gas measures 200 liters at 10°C and 640 torrs. What will be its volume at 740 torrs and 0°C?

Assignment Previewer

Close this window

heat energy #2 (271362)

About this Assignment

Description

Note the last multiple choice question is not in the curriculum, but it is interesting to discuss.

Instructions

NH3 ammonia = 17g/mol 1000 Liters = 1 meter cubed V rms = root mean squared velocity= average velocity

	pts
1	-

1. Hecht2 12.MC.002. [14744] At the temperature known as absolute zero
   - ○ translational atomic KE is zero
   - ○ atomic motion is at a minimum
   - ○ none of these
   - ○ all motion ceases
   - ○ time ceases

---

	pts
1	-

2. Hecht2 12.MC.006. [14748] If the temperature of a sealed chamber full of gas is increased, the pressure will
   - ○ increase proportionately
   - ○ first decrease and then increase
   - ○ none of these
   - ○ remain constant
   - ○ decrease proportionately

---

	pts
1	-

3. Hecht2 12.MC.009. [14751] Given that we have 17.0 g of ammonia gas (NH_3), the volume it occupies at STP is
   - ○ 17 liters
   - ○ none of these
   - ○ 22.4 liters
   - ○ 22.4×10^6 m^3
   - ○ 17 m^3

---

	pts
1	-

4. Hecht2 12.MC.010. [14752] According to Kinetic Theory, the molecules of a gas at a given temperature
   - ○ all move with a speed v_{rms}
   - ○ all move at speeds in excess of v_{rms}
   - ○ move at speeds above, at, and below v_{rms}
   - ○ all move at speeds less than v_{rms}

3.1-22

○ none of these

	pts
1	-

5. Hecht2 12.MC.012. [14754] A sample of gas is held at a constant pressure in a cylinder closed by a movable piston. If the volume is halved, how will the new *rms*-speed of the molecules compare with the original *rms*-speed? It will be

○ $\sqrt{2}$ times greater
○ 4 times greater
○ none of these
○ the same
○ 2 times greater

	pts
1	-

6. Hecht2 12.MC.013. [14755] A sample of gas is held at a constant pressure in a cylinder closed by a movable piston. If the volume is doubled, how will the new *rms*-speed of the molecules compare with the original *rms*-speed? It will be

○ none of these
○ 4 times greater
○ 2 times greater
○ $\sqrt{2}$ times greater
○ the same

	pts
1	-

7. Hecht2 12.MC.017. [14759] According to Kinetic Theory, the molecules of a gas at a given temperature

○ all have the same kinetic energy
○ all have the same direction of motion
○ none of these
○ all have the same momentum
○ all have the same speed

	pts
1	-

8. Hecht2 13.MC.001. [14873] Two bodies that are not initially in thermal equilibrium are placed in intimate contact. After a while the

○ temperature of the cooler one will rise the same number of kelvins as the temperature of the hotter one drops
○ amount of thermal energy contained by both bodies will be equal
○ thermal conductivity of each body will be the same
○ specific heats of both bodies will be equal
○ none of these

	pts
1	-

9. Hecht2 13.MC.002. [14874] An open beaker of pure water is gently boiling at atmospheric pressure. A thermometer held deep in the water will likely read a temperature

○ equal to 100°C
○ a little less than 100°C
○ equal to 212°C
○ none of these

3.1-23

Name ____________________

More HEAT/THERMAL Problems:

1. A 500 cm^3 container is filled with Cl_2 gas. How many moles of the gas are the in the container at STP? (remember to convert cm^3 to m^3)
2. A gas occupies 4.5 L at STP. What new volume will the gas occupy if its temperature is raised to 53^0C and the pressure changes to 1.75 atm?

3a. How much heat is required to change the temperature of 500 g of water from 10^0C to 50^0C? (sketch the heating curve)

3b. How much heat is required to change the temperature of 500 g of iron from 10^0C to 50^0C? (sketch the heating curve)

4. How much heat is required to change the temperature of 500. g of water from 10^0C to steam at 110^0C? (sketch the heating curve)
5. How much heat must be removed to cool 1.5 kg of water at 20^0C to ice at -10^0C? (sketch the cooling curve)
6. 12,500 Joules of heat energy is added to 300.g of water initially at 20.00^0C. What is the final temperature?

1. The temperature of an ideal gas is a measure of the gas molecules'

A. average velocity.

B. maximum velocity.

C. average kinetic energy.

D. total kinetic energy.

2. The pressure a gas exerts on a container wall is due to the

A. change in kinetic energy of the gas molecules as they strike the wall.

B. change in momentum of the gas molecules as they strike the wall.

C. average potential energy of the gas molecules.

D. force of repulsion between the gas molecules.

3. Some liquid is contained in a shallow dish that is open to the atmosphere. The rate of evaporation of the liquid does **not** depend on

A. the temperature of the liquid.

B. the temperature of the atmosphere.

C. the depth of the liquid.

D. the pressure of the atmosphere.

4. Two identical containers P and Q hold two different ideal gases at the same temperature. The number of moles of each gas is the same. The molecular weight of the gas in container P is twice that of the gas in Q. The ratio of the pressure in P to that of Q will be

A. $\frac{1}{2}$.

B. 1.

C. $\sqrt{2}$.

D. 2.

5. The temperature of an ideal gas is reduced. Which **one** of the following statements is true?

A. The molecules collide with the walls of the container less frequently.

B. The molecules collide with each other more frequently.

C. The time of contact between the molecules and the wall is reduced.

D. The time of contact between molecules is increased.

6. When a gas in a cylinder is compressed at constant temperature by a piston, the pressure of the gas increases. Consider the following three statements.

I. The rate at which the molecules collide with the piston increases.

II. The average speed of the molecules increases.

III. The molecules collide with each other more often.

Which statement(s) correctly explain the increase in pressure?

A. I only

B. II only

C. I and II only

D. I and III only

7. The volume and temperature of a sample of an ideal gas can be adjusted. Which combination of these changes will **always** result in a greater gas pressure?

	Volume	Temperature
A.	Increase	Increase
B.	Increase	Decrease
C.	Decrease	Increase
D.	Decrease	Decrease

8. When a gas is compressed at constant temperature, the pressure increases. This is because the molecules of the gas

A. repel each other.

B. are squashed together.

C. hit the walls of the container at a greater average speed.

D. hit the walls of the container more often in a given time.

9. A fixed volume of an ideal gas is at a temperature of 27 °C. In order to **double** the pressure at constant volume the temperature must be

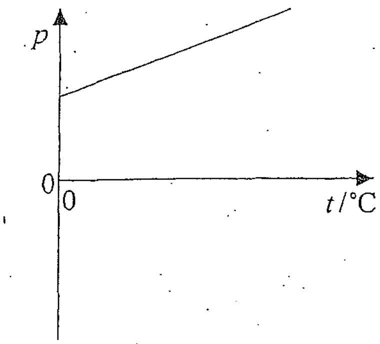
A. decreased to minus 123 °C.

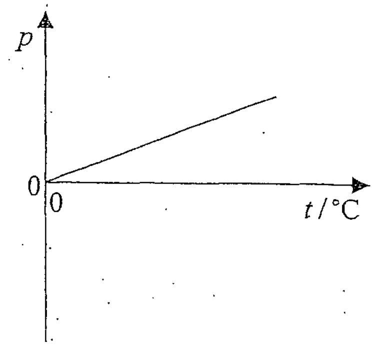
B. decreased to 13.5 °C.

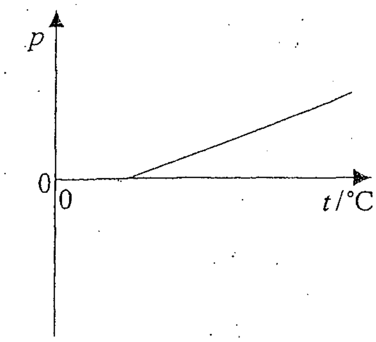
C. increased to 54 °C.

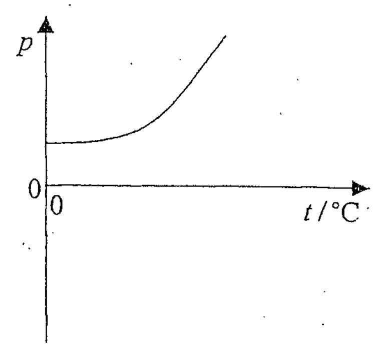
D. increased to 327 °C.

10 A fixed mass of an ideal gas is heated at constant volume. Which **one** of the following graphs best shows the variation with Celsius temperature t with pressure p of the gas?

A.


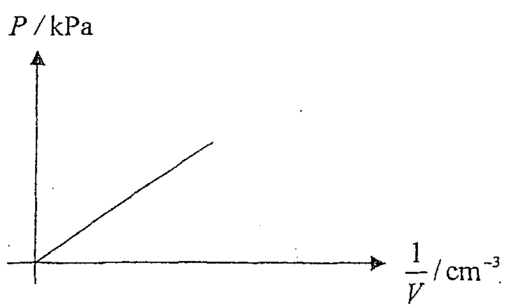
B.


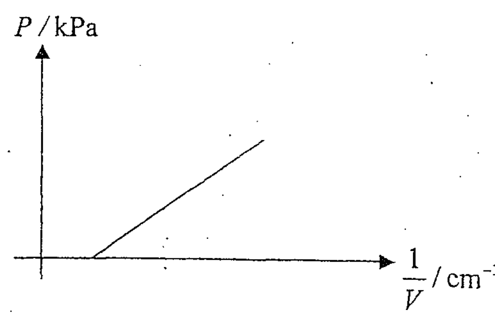
C.


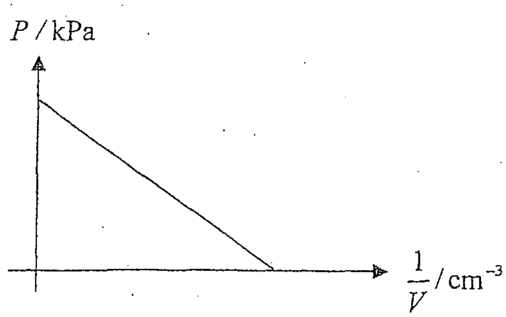
D.


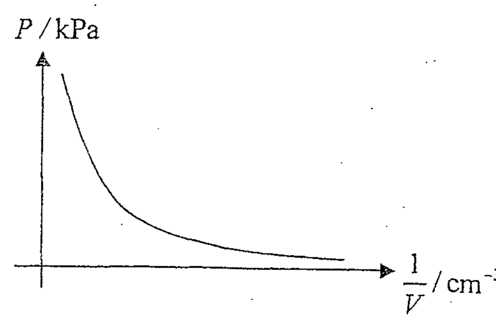
11 The pressure P, and volume V, of a sample of a gas are measured at constant temperature and a graph of P against $\frac{1}{V}$ is plotted.

Which **one** of the following graphs would be obtained if P is proportional to $\frac{1}{V}$ **and there is a systematic error in the measurement of P?**

A.


B.


C.


D.


12 The volume V, pressure P, and temperature T, of a fixed number of moles of an ideal gas are related by

$$\frac{PV}{T} = \text{constant}.$$

If the relationship between pressure and volume at constant temperature is investigated experimentally, which one of the following plots would produce a linear graph?

A. P against V

B. $\frac{1}{P}$ against $\frac{1}{V}$

C. P against $\frac{1}{V}$

D. No plot can produce a straight line

13 Two identical boxes X and Y each contain an ideal gas.

Box X	**Box Y**
n moles	$2n$ moles
temperature T	temperature $\frac{T}{3}$
pressure P_X	pressure P_Y

In box X there are n moles of the gas at temperature T and pressure P_X. In box Y there are $2n$ moles of the gas at temperature $\frac{T}{3}$ and pressure P_Y.

The ratio $\frac{P_X}{P_Y}$ is

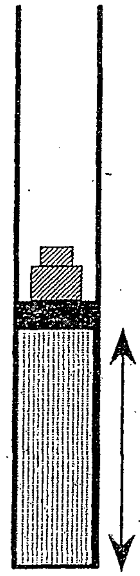
A. $\frac{2}{3}$.

B. $\frac{3}{2}$.

C. 2.

D. 3.

14. A gas is in a vertical cylinder fitted with a piston. Weights are placed on the piston. When the gas is at 27 °C the piston is in equilibrium at height h above the base of the cylinder as shown below.



To what value should the gas temperature be increased for the piston to be in equilibrium at a height $2h$ above the base?

A. 54 °C

B. 150 °C

C. 327 °C

D. 600 °C

15 When the volume of an enclosed gas is **increased** at constant temperature, the pressure exerted by the gas on the container wall **decreases**. Consider the following statements as possible explanations for this:

I. the average speed at which gas molecules strike the walls decreases.

II. the rate at which molecules strike a given area of the walls decreases.

The pressure decrease is explained by

A. I only.

B. II only.

C. I and II.

D. neither I nor II.

16. The equation of state for an ideal gas, $pV=nRT$, describes the behaviour of real gases

A. only at low pressures and large volumes.

B. only at high temperatures.

C. only at large volumes and large pressures.

D. at all pressures and volumes.

3.1-30

17. A container holds 20 g of neon (mass number 20) and also 8 g of helium (mass number 4).

What is the ratio $\frac{\text{number of atoms of neon}}{\text{number of atoms of helium}}$?

A. 0.4

B. 0.5

C. 2.0

D. 2.5

18 The source of the Sun's energy is

A. fission.

B. radioactivity.

C. fusion.

D. ionization.

19 The distance between the 0°C and 100°C marks on a mercury-in-glass thermometer is 20 cm. When the thermometer bulb is placed in a mixture of ice and salt, the mercury level is 4 cm below the 0°C mark. The temperature of the mixture is

A. +20°C.

B. +5°C.

C. −5°C.

D. −20°C.

20 A copper block is placed in thermal contact with a iron block at a higher temperature. The blocks have the same mass, and energy exchange with the surroundings is negligible.

Which of the following will be true of the magnitudes of the **internal energy change** and **temperature change** of each block when thermal equilibrium is reached?

	Changes in internal energy	**Changes in temperature**
A.	equal	equal
B.	unequal	equal
C.	equal	unequal
D.	unequal	unequal

3.1-31

21 Thermal energy is transferred through the glass windows of a house mainly by

A. conduction.

B. radiation.

C. conduction and convection.

D. radiation and convection.

C

22 Equal masses of water and alcohol, initially at different temperatures, are mixed. The specific heat capacity of water is **greater** than that of alcohol. The final temperature of the mixture will be

A. equal to the sum of the two original temperatures.

B. exactly midway between the two original temperatures.

C. closer to the original temperature of the water than of the alcohol.

D. closer to the original temperature of the alcohol than of the water.

23. A lead bullet is fired into an iron plate, where it deforms and stops. As a result, the temperature of the lead increases by an amount ΔT. For an identical bullet hitting the plate with **twice** the speed, what is the best estimate of the temperature increase?

C

A. ΔT

B. $\sqrt{2}\,\Delta T$

C. $2\,\Delta T$

D. $4\,\Delta T$

24 The kelvin temperature of an object is a measure of

A. the total energy of the molecules of the object.

B. the total kinetic energy of the molecules of the object.

C. the maximum energy of the molecules of the object.

D. the average kinetic energy of the molecules of the object.

25. The specific latent heat of fusion of a substance is defined as the amount of thermal energy required to change the phase of

A. the substance at constant temperature.

C

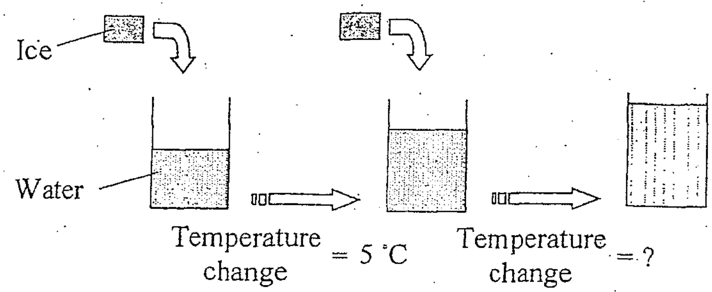
B. unit mass of the substance to liquid at constant temperature.

C. unit mass of the substance at constant temperature.

3.1-32

D. the substance to gas at constant temperature.

26 When a lump of ice was added to a beaker of warm water, the resulting water temperature was 5 °C less than the initial temperature of the warm water.



If another identical lump of ice is added to the same beaker, the temperature will

A. go down by another 5 °C.

B. not go down at all.

C. go down by more than 5 °C.

D. go down by less than 5 °C.

27. When two bodies are in contact, the **direction** of thermal energy transfer depends on their

A. surface areas.

B. masses.

C. specific heat capacities.

D. temperatures.

28 Jillian heats up her bath water by adding hot water at 80°C to 9 times that amount of water already in the bath, at 30°C. The best estimate for the final temperature of the water is

A. 35°C.

B. 40°C.

C. 45°C.

D. 50°C.

29. The specific latent heat of vaporization of a substance is the quantity of energy required to

A. raise the temperature of a unit mass of a substance by one degree Celsius.

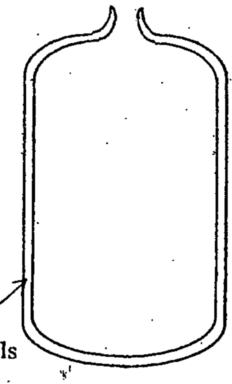
B. convert a unit mass of liquid to vapour at constant temperature and pressure.

C. convert a unit mass of solid to vapour at constant temperature and pressure.

3.1-31

D. convert a unit mass of liquid to vapour at a temperature of 100 °C and a pressure of one atmosphere.

30 A vacuum flask (or Dewar flask) is an insulated container useful for storing hot or cold liquids (coffee, tea, liquid nitrogen, *etc.*). In its construction a vacuum is used to minimise energy transfer with the environment.



The vacuum reduces

A. radiation, convection and conduction losses.

B. convection and conduction losses.

C. convection losses only.

D. radiation losses only.

31 Two different objects are in thermal contact with one another. The objects are at different temperatures. The temperatures of the two objects determine

A. the process by which thermal energy is transferred.

B. the heat capacity of each object.

C. the direction of transfer of thermal energy between the objects.

D. the amount of internal energy in each object.

32 A substance changes from a solid to a liquid at **constant temperature**. Which **one** of the following correctly describes the changes in the average interatomic potential energy and the average kinetic energy of the molecules during the process?

	Average interatomic potential energy	Average kinetic energy
A.	Increases	Remains constant
B.	Remains constant	Increases
C.	Increases	Increases
D.	Remains constant	Remains constant

3.1-32

33 A lead bullet is fired into an iron plate, where it deforms and stops. As a result, the temperature of the lead increases by an amount ΔT. For a lead bullet having **twice** the mass but the same speed of impact, what would be the best estimate of its temperature increase?

A. $\frac{1}{2}\Delta T$

B. ΔT

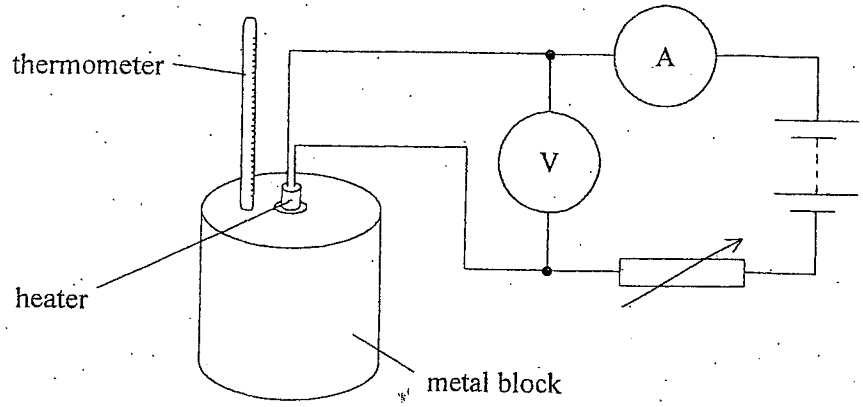
C. $\sqrt{2}\,\Delta T$

D. $2\,\Delta T$

34 An engine takes in an amount E of thermal energy and, as a result, does an amount W of useful work. An amount H of thermal energy is ejected. The law of conservation of energy and the efficiency of the engine are given by which of the following?

	Law of conservation of energy	Efficiency
A.	$E = W + H$	W
B.	$E = W + H$	$\frac{W}{E}$
C.	$E + H = W$	$\frac{W}{H}$
D.	$E + H = W$	$\frac{W}{(E-H)}$

The following diagram refers to questions 15 and 16.



The specific heat capacity of a metal block of mass m is determined by placing a heating coil in its centre, as shown in the diagram above.

The block is heated for time t and the maximum temperature change recorded is $\Delta\theta$. The ammeter and voltmeter readings during the heating are I and V respectively.

35 The specific heat capacity is best calculated using which **one** of the following expressions?

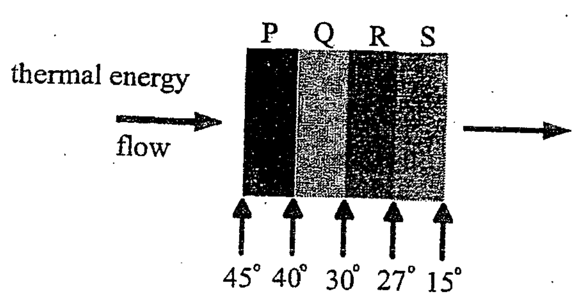
A. $c = \dfrac{VIt}{m\Delta\theta}$

B. $c = \dfrac{VI}{m\Delta\theta}$

C. $c = \dfrac{m\Delta\theta}{VI}$

D. $c = \dfrac{m\Delta\theta}{VIt}$

36 The diagram shows four rectangular slabs of different materials labelled, P, Q, R and S. They have equal thickness and are placed side by side, in contact. Thermal energy flows from left to right and the steady-state temperatures of the interfaces are given. The material with the largest thermal conductivity is



A. P.

B. Q.

C. R.

D. S.

3.1-34

https://ibphysics2016.wikispaces.com/Topic+3+%28Core%29

Topic 3: Thermal physics
3.2 – Modeling a gas — Option B2

Essential idea: The properties of ideal gases allow scientists to make predictions of the behaviour of real gases.

Nature of science: Collaboration: Scientists in the 19th century made valuable progress on the modern theories that form the basis of thermodynamics, making important links with other sciences, especially chemistry. The scientific method was in evidence with contrasting but complementary statements of some laws derived by different scientists. Empirical and theoretical thinking both have their place in science and this is evident in the comparison between the unattainable ideal gas and real gases.

1

Topic 3: Thermal physics
3.2 – Modeling a gas

Understandings:
- Pressure
- Equation of state for an ideal gas
- Kinetic model of an ideal gas
- Mole, molar mass and the Avogadro constant
- Differences between real and ideal gases

Applications and skills:
- Solving problems using the equation of state for an ideal gas and gas laws
- Sketching and interpreting changes of state of an ideal gas on pressure–volume, pressure–temperature and volume–temperature diagrams
- Investigating at least one gas law experimentally

2

Topic 3: Thermal physics
3.2 – Modeling a gas

Guidance:
- Students should be aware of the assumptions that underpin the molecular kinetic theory of ideal gases
- Gas laws are limited to constant volume, constant temperature, constant pressure and the ideal gas law
- Students should understand that a real gas approximates to an ideal gas at conditions of low pressure, moderate temperature and low density

Data booklet reference:
- $p = F / A$
- $n = N / N_A$
- $pV = nRT$
- $\bar{E}_K = (3/2)\, k_B T = (3/2)\, RT / N_A$

3

Topic 3: Thermal physics
3.2 – Modeling a gas

Theory of knowledge:
- When does modelling of "ideal" situations become "good enough" to count as knowledge?

Utilization:
- Transport of gases in liquid form or at high pressures/densities is common practice across the globe. Behaviour of real gases under extreme conditions needs to be carefully considered in these situations.
- Consideration of thermodynamic processes is essential to many areas of chemistry (see *Chemistry* sub-topic *1.3*)
- Respiration processes (see *Biology* sub-topic *D.6*)

4

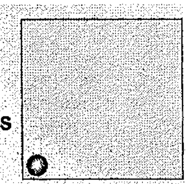
Topic 3: Thermal physics
3.2 – Modeling a gas

Aims:

- **Aim 3:** this is a good topic to make comparisons between empirical and theoretical thinking in science
- **Aim 6:** experiments could include (but are not limited to): verification of gas laws; calculation of the Avogadro constant; virtual investigation of gas law parameters not possible within a school laboratory setting

Topic 3: Thermal physics
3.2 – Modeling a gas

Pressure



- Consider a gas molecule confined in a closed box as shown.
- Since the molecule's direction is always changing, it is accelerating, and thus feeling a force from the walls of the box.
- From Newton's third law, the molecule is exerting an equal and opposite force on the walls of the box.
- The walls of the box feel a **pressure** p, given by the formula below:

$p = F / A$	pressure

- From the formula we can see that the units of pressure are ($N\ m^{-2}$), also known as Pascals (Pa).

Topic 3: Thermal physics
3.2 – Modeling a gas

Pressure

$p = F / A$	pressure

PRACTICE:
A 150-kg man stands on one foot on some ice. Given that his foot is about 9.0 cm by 10. cm in rectangular cross-section, find the pressure on the ice.
SOLUTION:

- First, find the force:

$$F = mg = 150(10) = 1500 \text{ n.}$$

- Then find the area:

$$A = LW = (.09)(.10) = 0.009 \text{ m}^2.$$

- Finally

$$p = F / A = 1500 / .009 = 170000 \text{ N m}^{-2} = 170000 \text{ Pa.}$$

Topic 3: Thermal physics
3.2 – Modeling a gas

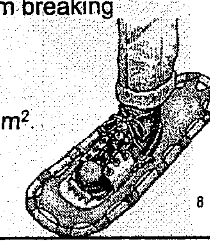
Pressure

$p = F / A$	pressure

PRACTICE:
If the ice is thin enough that it will break under a pressure of 1.0×10^5 Pa, what should be the area of a snowshoe that will just prevent him from breaking through when on one foot?
SOLUTION:

- From $p = F / A$ we have:

$$A = F / p = 1500 / 100000 = 0.015 \text{ m}^2.$$



3.2-2

Topic 3: Thermal physics
3.2 – Modeling a gas

The kinetic model of an ideal gas

- An **ideal gas** is an imaginary gas that is used to model real gases, and has the following properties:

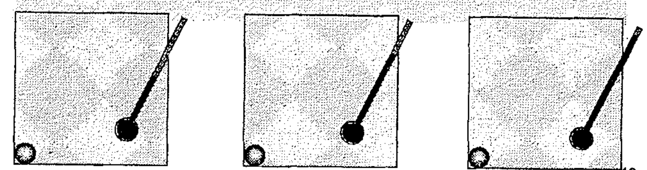
The molecules that make up an ideal gas...
*...are **identical perfect spheres**.*
*...are **perfectly elastic** – they don't lose any kinetic energy during their collisions with each other, or the walls of their container.*
*...have **no intermolecular forces** – their potential energy does not change.*
*...are so **small** that their volume is much smaller than the volume of their container.*

9

Topic 3: Thermal physics
3.2 – Modeling a gas

The kinetic model of an ideal gas

- Just as temperature was a measure of the random kinetic energy of molecules for solids and liquids, so it is for an ideal gas.
- If the temperature of a gas increases, so does the average speed (and hence kinetic energy) of the molecules.

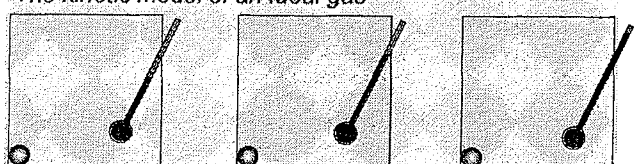


low T | medium T | high T

10

Topic 3: Thermal physics
3.2 – Modeling a gas

The kinetic model of an ideal gas



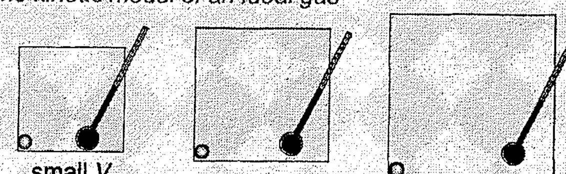
low T, low p | medium T, medium p | high T, high p

- Looking at this animation again we can see that if the speed of the molecules increases, then the number of collisions with the container walls will also increase.
- Thus the pressure will increase if the temperature increases.

11

Topic 3: Thermal physics
3.2 – Modeling a gas

The kinetic model of an ideal gas



small V, high p | medium V, medium p | large V, low p

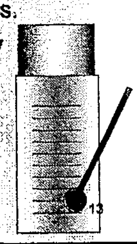
- Consider small, medium and large containers.
- In a smaller volume the molecules have less distance to travel to hit a wall. Thus the wall is hit more often.
- Thus the pressure will be bigger if the volume is smaller.

12

Topic 3: Thermal physics
3.2 – Modeling a gas

The kinetic model of an ideal gas

- Consider a syringe full of an ideal gas.
- If we make the volume less we see that the temperature will increase.
- Since the plunger exerts a force on the gas, and executes a displacement, it does work on the gas.
- From the work-kinetic energy theorem we know that if we do work on the gas, its kinetic energy must increase.
- Thus its speed will increase, which means its temperature increases.
- On the other hand, if the process is reversed the gas will do the work, lose E_K and cool.



13

Topic 3: Thermal physics
3.2 – Modeling a gas

The kinetic model of an ideal gas

The temperature of an ideal gas is reduced. Which one of the following statements is true?

(A) The molecules collide with the walls of the container less frequently.

B. The molecules collide with each other more frequently.

C. The time of contact between the molecules and the wall is reduced.

D. The time of contact between molecules is increased.

- Temperature is a measure of the E_K of the gas.
- Reducing the E_K reduces the frequency of collisions.
- For <u>perfectly elastic</u> collisions (as in an ideal gas) contact time is zero regardless of E_K

14

Topic 3: Thermal physics
3.2 – Modeling a gas

2 6
C
Carbon
12.011

The mole and molar mass

- Recall from the periodic table of the elements that each element has certain numbers associated with it.
- We define the mole of a homogeneous substance as follows:

KEY
Atomic Number
Period
Symbol
Atomic Weight
Xx

1 mole is the number of atoms of an element that will have a mass in grams equal to its gram atomic weight.	definition of mole and molar mass

EXAMPLE: Find the mass (in kg) of one mole of carbon.

SOLUTION:

- From the periodic table we see that it is just 1 mole C = 12.011 grams = 0.012011 kg.

15

Topic 3: Thermal physics
3.2 – Modeling a gas

The mole and molar mass

PRACTICE:
What is the *gram atomic weight* of oxygen?

SOLUTION:
It is 15.9994 g, or if you prefer,
(15.9994 g)(1 kg / 1000 g) = 0.015994 kg.

2 8
O
Oxygen
15.9994

PRACTICE:
What is the molar mass of phosphorus in kilograms?

- From the periodic table we see that the molar mass of phosphorus is 30.973762 grams.
- The molar mass in kilograms is 0.030973762 kg.

3 15
P
Phosphorus
30.973762

16

Topic 3: Thermal physics
3.2 – Modeling a gas

The mole and molar mass

1 H Hydrogen 1.00794 1
2 O Oxygen 15.9994 8

PRACTICE: Water is made up of 2 hydrogen atoms and 1 oxygen atom and has a molecular formula given by H_2O. Find
(a) the gram atomic weight of water.
(b) the mass in grams of 1 mole of water.
(c) how many moles of hydrogen and oxygen there are in 1 mole of water.
SOLUTION:
(a) The GAW of H_2O is given by
2(1.00794) + 1(15.9994) = 18.01528 g per mole.
(b) Thus the mass of 1 mole of H_2O is 18.01528 g.
(c) Since each mole of H_2O has 2H and 1O, there are 2 moles of H and 1 mole of O for each mole of water.

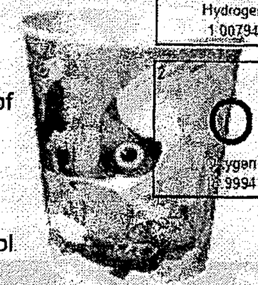
17

Topic 3: Thermal physics
3.2 – Modeling a gas

The mole and molar mass

1 H Hydrogen 1.00794 1
2 O Oxygen 15.9994 8

PRACTICE:
Suppose we have 12.25 g of water in a Dixie™ Cup? How many moles of water does this amount to?



SOLUTION:
•We determined that the GAW of H_2O is 18.01528 g per mole in the previous problem.
•Thus
(12.25 g)(1 mol / 18.01528 g)
= 0.6800 mol

FYI
•Maintain your vigilance regarding significant figures!

18

Topic 3: Thermal physics
3.2 – Modeling a gas

3 P Phosphorus 30.973762 15
2 C Carbon 12.011 6

The Avogadro constant
•It turns out the a mole of carbon (12 g) and a mole of phosphorus (31 g) **has the same number of atoms**.
•This means that 30.973762 g of P has the same number of atoms and 12.011 g of C.
•That number N_A is given here:

$N_A = 6.02\times10^{23}$ molecules. **the Avogadro constant**

EXAMPLE: How many atoms of P are there in 31.0 g of it? How many atoms of C are there in 12.0 g of it?
SOLUTION:
•There are $N_A = 6.02\times10^{23}$ atoms of P in 31.0 g of it.
•There are $N_A = 6.02\times10^{23}$ atoms of C in 12.0 g of it.

19

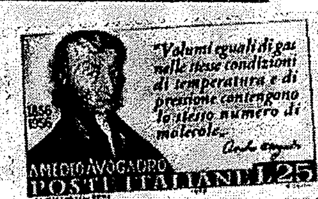
Topic 3: Thermal physics
3.2 – Modeling a gas

3 P Phosphorus 30.973762 15
2 C Carbon 12.011 6

The Avogadro constant

$N_A = 6.02\times10^{23}$ molecules. **the Avogadro constant**

•To find the number of atoms in a sample, simply convert sample to moles, then use the conversion
1 mol = 6.02×10^{23} molecules.



EXAMPLE: How many atoms of P are there in 145.8 g of it?
SOLUTION: It is best to start with the given quantity.
(145.8 g)(1 mol / 30.984 g)(6.02×10^{23} atoms / 1 mol)
= 2.83×10^{24} atoms of P.

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Topic 3: Thermal physics
3.2 – Modeling a gas

C — Carbon 12.011 (2, 6)

The Avogadro constant

- To find the number of moles n in a sample containing N atoms, use this formula:

$n = N / N_A$	the molar ratio

EXAMPLE: A sample of carbon has 1.28×10^{24} atoms as counted by Marvin the Paranoid Android.

a) How many moles is this?

b) What is its mass?

SOLUTION: It is best to start with the given quantity.

a) $(1.28\times10^{24}$ atoms$)(1$ mol$/6.02\times10^{23}$ atoms$)$ $= 2.13$ mol.

b) $(2.13$ mol$)(12.011$ g / mol$) = 25.5$ g of C.

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Topic 3: Thermal physics
3.2 – Modeling a gas

Equation of state for an ideal gas

- Without proof, here is the **equation of state** for an ideal gas.

$pV = nRT$ — $R = 8.31$ J / mol·K is the **universal gas constant**	equation of state of an ideal gas

- We will explain what an ideal gas is a bit later...
- The variables p (pressure), V (volume), n (number of moles), and T (temperature) are all called the four **state variables**.
- p is measured in Pascals or Nm^{-2}.
- V is measured in m^3.
- T is measured in K.

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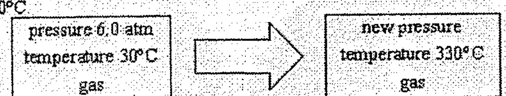
Topic 3: Thermal physics
3.2 – Modeling a gas

Equation of state for an ideal gas

An ideal gas is kept in a container of fixed volume at a temperature of 30°C and a pressure of 6.0 atm. The gas is heated at constant volume to a temperature of 330°C.



The new pressure of the gas is about

A. 0.60 atm B. 3.0 atm (C) 12 atm D. 66 atm

- Use $pV = nRT$.
- From $T(K) = T(°C) + 273$

$T_i = 30 + 273 = 303$ K.

$T_f = 330 + 273 = 603$ K.

- $V_i = V_f$.

$p_iV_i = nRT_i$, $p_fV_f = nRT_f$.

$\frac{p_fV_f}{p_iV_i} = \frac{nRT_f}{nRT_i}$

$p_f = p_iT_f / T_i$

$p_f = (6)(603) / 303 = 12$

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Topic 3: Thermal physics
3.2 – Modeling a gas

Equation of state for an ideal gas

The internal volume of a gas cylinder is 2.0×10^{-2} m^3. An ideal gas is pumped into the cylinder until the pressure becomes 20 MPa at a temperature of 17°C.

Determine

(i) the number of moles of gas in the cylinder,

- For an ideal gas use $pV = nRT$.
- WANTED: n, the number of moles.
- GIVEN: $p = 20\times10^6$ Pa, $V = 2.0\times10^{-2}$ m^3.
- From $T(K) = T(°C) + 273$

$T(K) = 17 + 273 = 290$ K.

- Then $n = pV / (RT)$

$n = (20\times10^6)(2\times10^{-2}) / [(8.31)(290)]$

$n = 170$ mol.

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Topic 3: Thermal physics
3.2 – Modeling a gas

Equation of state for an ideal gas

The internal volume of a gas cylinder is 2.0×10^{-2} m^3. An ideal gas is pumped into the cylinder until the pressure becomes 20 MPa at a temperature of 17°C.

Determine

(ii) the number of gas atoms in the cylinder.

- Use $n = N / N_A$ where $N_A = 6.02 \times 10^{23}$ atoms / mol.
- Then $N = n N_A$.

$N = 170 \text{ mol} \times \frac{6.02 \times 10^{23} \text{ atoms}}{\text{mol}}$

$N = 1.0 \times 10^{26}$ atoms.

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Topic 3: Thermal physics
3.2 – Modeling a gas

Differences between real and ideal gases

- Recall the properties of an ideal gas:

The molecules that make up an ideal gas…
*…are **identical perfect spheres**.*
*…are **perfectly elastic** – they don't lose any kinetic energy during their collisions with each other, or the walls of their container.*
*…have **no intermolecular forces** – their potential energy does not change.*
*…are so **small** that their volume is much smaller than the volume of their container.*

- The kinetic theory of gases is, of course, a **model**.
- As such, it doesn't apply *perfectly* to real gases.

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Topic 3: Thermal physics
3.2 – Modeling a gas

Differences between real and ideal gases

- Here are the properties of a real gas.

The molecules that make up a real gas…
…are not identical perfect spheres.
…are not perfectly elastic.
…have intermolecular forces.
…are relatively large.

FYI

- Real gases are often polyatomic (N_2, O_2, H_2O, NH_4, etc.) and thus not spherical.
- Ideal gases cannot be liquefied, but real gases have intermolecular forces and non-zero volume, so they can be liquefied.

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Topic 3: Thermal physics
3.2 – Modeling a gas

Differences between real and ideal gases

The equation of state for an ideal gas, $pV = nRT$, describes the behaviour of real gases

(A) only at low pressures and large volumes.

B. only at high temperatures.

C. only at large volumes and large pressures.

D. at all pressures and volumes.

- Under high pressure or low volume real gases' intermolecular forces come into play.
- Under low pressure or large volume real gases' obey the equation of state.

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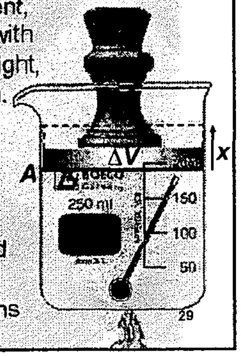
Topic 3: Thermal physics
3.2 – Modeling a gas

Constant pressure process – ***isobaric process***

- In an **isobaric process**, *p does not change*.
- As an example of an isobaric experiment, suppose we take a beaker that is filled with an ideal gas, and stopper it with a gas-tight, frictionless cork and a weight, as shown.
- The weight F causes a pressure in the gas having a value given by $p = F / A$, where A is the area of the cork in contact with the gas.
- If we now heat up the gas it will expand against the cork, pushing it upward.
- Since neither F nor A change, p remains constant.



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Topic 3: Thermal physics
3.2 – Modeling a gas

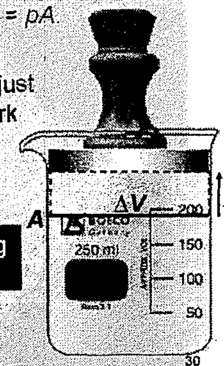
Constant pressure process – ***work done by a gas***

- From the previous slide: $p = F / A \rightarrow F = pA$.
- From the picture note that $\Delta V = Ax$.
- Recall the work W done by the gas is just the force F it exerts on the weighted cork times the displacement x it moves the cork. Thus

$$W = Fx = pAx = p\Delta V.$$

$W = p\Delta V$	work done by expanding gas (constant p)

FYI
- If $\Delta V > 0$ (gas expands) then $W > 0$.
- If $\Delta V < 0$ (gas contracts) then $W < 0$.



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Topic 3: Thermal physics
3.2 – Modeling a gas

Constant pressure process – ***isobaric process***

EXAMPLE:
Show that for an isolated ideal gas $V \propto T$ during an isobaric process.

SOLUTION: Use $pV = nRT$. Then

$$V = (nR / p)T.$$

- Isolated means n is constant (no gas is added to or lost from the system).
- Isobaric means p is constant.
- Then n and P are constant (as is R). Thus

$$V = (nR / p)T = (\text{CONST})T$$
$$V \propto T. \text{ (isobaric process)}$$

FYI
- The symbol $\propto$ means "is proportional to."

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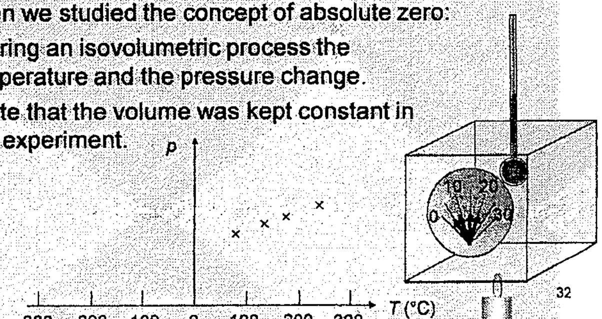
Topic 3: Thermal physics
3.2 – Modeling a gas

Constant volume process – ***isovolumetric process***

- In an **isovolumetric process**, *V does not change*.
- We have already seen an isovolumetric experiment when we studied the concept of absolute zero:
- During an isovolumetric process the temperature and the pressure change.
- Note that the volume was kept constant in this experiment.



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Topic 3: Thermal physics
3.2 – Modeling a gas

Constant volume process – ***isovolumetric process***

EXAMPLE:
Show that for an isolated ideal gas $p \propto T$ during an isovolumetric process.
SOLUTION:
•Use $pV = nRT$. Then

$$p = (nR/V)T.$$

•Isolated means n is constant (no gas is added to or lost from the system).
•Isovolumetric means that V is constant.
•Then n and V are constant (as is R). Thus

$$p = (nR/V)T = (\text{CONST})T$$

$$p \propto T. \text{ (isovolumetric process)}$$

FYI •Isovolumetric is sometimes called isochoric.

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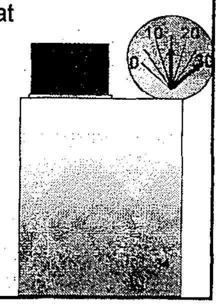
Topic 3: Thermal physics
3.2 – Modeling a gas

Why do we wait before recording our values?

Constant temperature process – ***isothermal process***
•In an **isothermal process**, T does not change.
EXAMPLE: A graduated syringe which is filled with air is placed in an ice bath and allowed to reach the temperature of the water. Demonstrate that

$$p_1V_1 = p_2V_2.$$



SOLUTION:
•Record initial states after a wait:
$p_1 = 15$, $V_1 = 10$, and $T_1 = 0°C$.
•Record final states after a wait:
$p_2 = 30$, $V_2 = 5$, and $T_2 = 0°C$.
$p_1V_1 = 15(10) = 150$.
$p_2V_2 = 30(5) = 150$.
•Thus $p_1V_1 = p_2V_2$.

Topic 3: Thermal physics
3.2 – Modeling a gas

Constant temperature process – ***isothermal process***

PRACTICE:
Show that for an isolated ideal gas $p_1V_1 = p_2V_2$ during an isothermal process.

SOLUTION:
•From $pV = nRT$ we can write
$p_1V_1 = nRT_1$
$p_2V_2 = nRT_2$.
•Isolated means n is constant.
•Isothermal means T is constant so $T_1 = T_2 = T$.
•Obviously R is constant.
•Thus

$$p_1V_1 = nRT = p_2V_2. \text{ (isothermal)}$$

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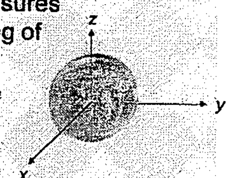
Topic 3: Thermal physics
3.2 – Modeling a gas

Sketching and interpreting state change graphs
•Perhaps you have enjoyed the pleasures of analytic geometry and the graphing of surfaces in 3D.
•The three variables of a surface are x, y, and z, and we can describe any surface using the "state" variables x, y, and z:



•The "equation of state" of a sphere is $x^2 + y^2 + z^2 = r^2$, where r is the radius of the sphere.
FYI
•We "built" the 3D sphere with layers of 2D circles.
•We have transformed a 3D surface into a stack of 2D surfaces.

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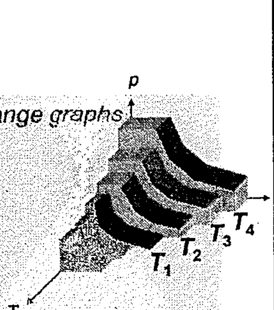
Topic 3: Thermal physics
3.2 – Modeling a gas

Sketching and interpreting state change graphs

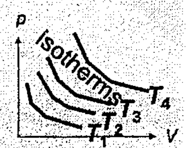
- The three state variables of a gas (if *n* is kept constant) are analogous.
- We can plot the three variables *p*, *V*, and *T* on mutually perpendicular axes like this:



- We have made layers in *T*. Thus each layer has a single temperature.

FYI

- Each layer is an isotherm.
- The 3D graph (above) can then be redrawn in its simpler 2D form (below) without loss of information.



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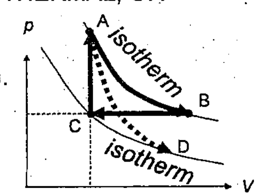
Topic 3: Thermal physics
3.2 – Modeling a gas

Sketching and interpreting state change graphs

- A **thermodynamic process** involves moving from one state to another state. This could involve changing any or even all of the state variables (*p*, *V*, or *T*).

EXAMPLE: In the *p*-*V* graph shown, identify each process type as ISOBARIC, ISOTHERMAL, OR ISOVOLUMETRIC (isochoric).



SOLUTION:

- A→B is isothermal (constant *T*).
- B→C is isobaric (constant *p*).
- C→A is isochoric (constant *V*).
- We will only have two states change at a time. Phew!

FYI • The purple line shows all three states changing.

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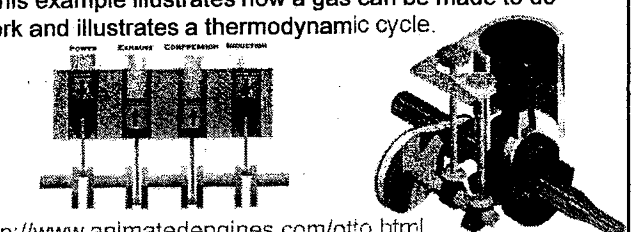
Topic 3: Thermal physics
3.2 – Modeling a gas

Sketching and interpreting state change graphs

EXAMPLE: An internal combustion engine is an example of a heat engine that does useful work on the environment. A four-stroke engine is animated here.

- This example illustrates how a gas can be made to do work and illustrates a thermodynamic cycle.



http://www.animatedengines.com/otto.html
http://chemcollective.org/activities/simulations/engine

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Topic 3: Thermal physics
3.2 – Modeling a gas

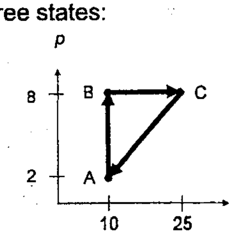
Sketching and interpreting state change graphs

- A **thermodynamic cycle** is a set of processes which ultimately return a gas to its original state.

EXAMPLE: A fixed quantity of a gas undergoes a cycle by changing between the following three states:

State A: (p = 2 Pa, V = 10 m^3)
State B: (p = 8 Pa, V = 10 m^3)
State C: (p = 8 Pa, V = 25 m^3)

Each process is a straight line, and the cycle goes like this: A→B→C→A.
Sketch the complete cycle on a *p*-*V* diagram.



SOLUTION:

- Scale your axes and plot your points...

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Topic 3: Thermal physics
3.2 – Modeling a gas

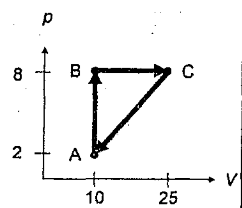
Sketching and interpreting state change graphs

EXAMPLE: A fixed quantity of a gas undergoes the cycle shown here (from the last example):
(a) Find the work done during the process A→B.
(b) Find the work done during the process B→C.

SOLUTION: Use $W = p\Delta V$.

(a) From A to B:
$\Delta V = 0$. Thus the $W = 0$.

(b) From B to C:
$\Delta V = 25 - 10 = 15$;
$p = 8$.
Thus $W = p\Delta V = 8(15) = 120$ J.



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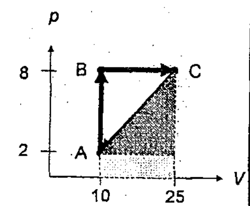
Topic 3: Thermal physics
3.2 – Modeling a gas

Sketching and interpreting state change graphs

EXAMPLE: A fixed quantity of a gas undergoes the cycle shown here (from the last example):
(c) Find the work done during the process C→A.

SOLUTION:
- Observe that ΔV is <u>negative</u> when going from C ($V = 25$) to A ($V = 10$).
- Observe that p is NOT constant so $W \neq p\Delta V$.
- W = *Area* under the p-V diagram.
  = - [(2)(15) + (1/2)(6)(15)]
  = - 75 J.



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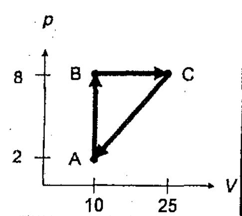
Topic 3: Thermal physics
3.2 – Modeling a gas

Sketching and interpreting state change graphs

EXAMPLE: A fixed quantity of a gas undergoes the cycle shown here (from the last example):
(d) Find the work done during the cycle A→B→C→A.

SOLUTION:
(d) Just total up the work done in each process.
- $W_{A\to B} = 0$ J.
- $W_{B\to C} = {}^{+}120$ J.
- $W_{C\to A} = -75$ J.
- $W_{cycle} = 0 + 120 - 75 = {}^{+}45$ J.



FYI •Because W_{cycle} is positive, work is done <u>on</u> the external environment during each cycle.

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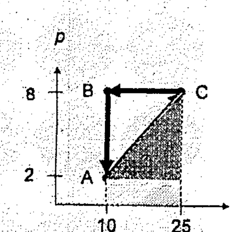
Topic 3: Thermal physics
3.2 – Modeling a gas

Sketching and interpreting state change graphs

PRACTICE:
Find the total work done if the previous cycle is reversed.

SOLUTION:
- We want the cycle A→C→B→A.
- $W_{A\to C}$ = *Area*
  = ${}^{+}$[(2)(15) + (1/2)(6)(15)] = ${}^{+}75$ J.
- $W_{C\to B} = P\Delta V = 8(10-25) = {}^{-}120$ J.
- $W_{B\to A} = 0$ J (since $\Delta V = 0$).
- $W_{cycle} = 75 - 120 + 0 = {}^{-}45$ J.



FYI •Reversing the cycle reverses the sign of the work.

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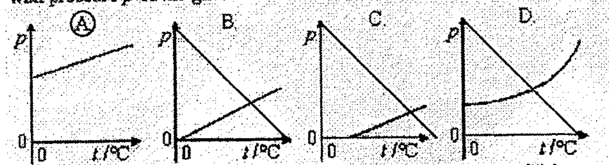
Topic 3: Thermal physics
3.2 – Modeling a gas

Sketching and interpreting state change graphs

A fixed mass of an ideal gas is heated at constant volume. Which one of the following graphs best shows the variation with Celsius temperature t with pressure p of the gas?



- Fixed mass and constant volume means n and V are constant. Thus
- $pV = nRT \rightarrow p = (nR/V)T \rightarrow p = (CONST)T$. *(LINEAR)*
- Since the t axis is in °C, but T is in Kelvin, the horizontal intercept must be NEGATIVE…

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Topic 3: Thermal physics
3.2 – Modeling a gas

Sketching and interpreting state change graphs

The graph below shows the variation with absolute temperature T of the pressure p of one mole of an ideal gas having a volume V. R is the molar gas constant.

- $p = 0$ at absolute zero.

- From $pV = nRT$:
- $p = (1R/V)T$:

Which of the following is the best interpretation of the intercept on the temperature axis and the gradient of the graph?

	Intercept on temperature axis / K	Gradient of graph
A.	−273	R/V
(B)	0	R/V
C.	0	V/R
D.	−273	V/R

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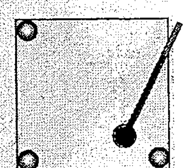
Topic 3: Thermal physics
3.2 – Modeling a gas

Average kinetic/internal energy of an ideal gas

- Since ideal gases have no intermolecular forces, their internal energy is stored completely as kinetic energy.
- The individual molecules making up an ideal gas all travel at different speeds.



- Without proof, the **average kinetic energy** $\bar{E}_K$ of each ideal gas molecule has the following forms:

$\bar{E}_K = (3/2)\, k_B T = 3RT / [\,2N_A\,]$
Where $k_B = 1.38\times10^{-23}$ J K^{-1}.

Average kinetic energy of ideal gas

- k_B is called the **Boltzmann constant**.

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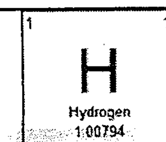
Topic 3: Thermal physics
3.2 – Modeling a gas



Average kinetic/internal energy of an ideal gas

$\bar{E}_K = (3/2)\, k_B T = 3RT / [\,2N_A\,]$
Where $k_B = 1.38\times10^{-23}$ J K^{-1}.

Average kinetic energy of ideal gas

EXAMPLE: 2.50 moles of hydrogen gas is contained in a fixed volume of 1.25 m^3 at a temperature of 175 °C.

a) What is the average kinetic energy of each atom?

b) What is the total internal energy of the gas?

SOLUTION: T(K) = 175 + 273 = 448 K.

a) $\bar{E}_K = (3/2)\, k_B T = (3/2)(1.38\times10^{-23})(448) = 9.27\times10^{-21}$ J.

b) From $n = N / N_A$ we get $N = nN_A$.

$N = (2.50 \text{ mol})(6.02\times10^{23} \text{ atoms / mol}) = 1.51\times10^{24}$ atm.

$E_K = N\bar{E}_K = (1.51\times10^{24})(9.27\times10^{-21} \text{ J}) = 14000$ J.

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Topic 3: Thermal physics
3.2 – Modeling a gas

H
1 1
Hydrogen
1.00794

Average kinetic/internal energy of an ideal gas

$\bar{E}_K = (3/2)\ k_B T = 3RT / [\ 2N_A\ ]$ Where $k_B = 1.38\times10^{-23}$ J K^{-1}.	Average kinetic energy of ideal gas

EXAMPLE: 2.50 moles of hydrogen gas is contained in a fixed volume of 1.25 m^3 at a temperature of 175 °C.

c) What is the pressure of the gas at this temperature?

SOLUTION: T(K) = 175 + 273 = 448 K.

c) Use $pV = nRT$: Then

$$p = nRT / V$$
$$= 2.50\times8.31\times448 / 1.25$$
$$= 7450 \text{ Pa.}$$

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Topic 3.2 – Modeling a gas **Formative Assessment**

NAME: ______________________ TEAM:__

THIS IS A PRACTICE ASSESSMENT. Show formulas, substitutions, answers (in spaces provided) and units!

1. A 17.5-pound bowling ball having a mass of 7.95 kg is placed on a dime having a diameter of 1.75 cm. The ball-dime combo is then placed on the floor. What is the pressure in N m^{-2} exerted on the floor? 1. ______________

The following questions are about an ideal gas.

2. State the equation of state for an ideal gas. 2. ______________

3. List the state variables for an ideal gas. 3. ______________

4. An ideal gas is kept in a fixed volume at a temperature of 25 °C and a pressure of 45 kPa. The gas is then heated at constant volume to a temperature of 50 °C. Determine its new pressure. 4. ______________

5. List the four assumptions of the kinetic model of an ideal gas.

______________ ______________

______________ ______________

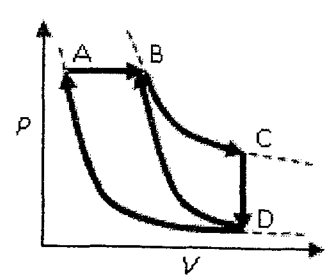
The internal volume of a gas cylinder is 4.50×10^{-2} m^3. The cylinder head has a diameter of 1.25 cm. An ideal gas is pumped into the cylinder until the pressure becomes 650. kPa. The temperature of the gas is 19.5 °C.

6. What force does the gas exert on the cylinder head? 6. ______________

7. Determine how many moles of the gas are there in the cylinder. 7. ______________

8. Determine the number of gas atoms in the cylinder. 8. ______________

Consider the p-V diagram to the right. Answer the following questions. All states will be designated with a single letter. All processes will be designated with two letters (e.g.: AD).



9. Of the two states B and D, which is at the higher temperature? 9. __________

10. Of the two states A and C, which is at the higher temperature? 10. __________

3.2-15

11. Which process is an isothermal expansion? 11. ____________

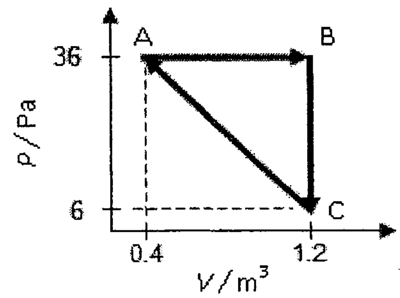
12. Which process is isobaric? Is it an expansion or a contraction? 12. ____________

____

13. Which process is isochoric? Is the gas cooling or warming during this process? 13. ____________

____

Consider the p-V diagram to the right for the following questions:



14. Find the work done during the process AB. Is this work done by the gas, or on the gas? 14. ____________

____

15. Find the work done during the process BC. 15. ____________

16. Find the work done during the process CA. 16. ____________

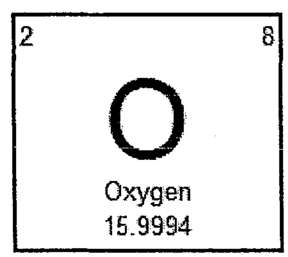
____

17. Find the work done during the entire cycle. Is this work done by the gas, or on the gas?

17. ____________

____

In the atmosphere oxygen generally occurs in the diatomic form as O_2 or in the triatomic form as O_3 (called ozone).



18. How many oxygen atoms are there in 2.5 mol of the diatomic form?

18. ____________

19. How many ozone molecules are there in 2.5 mol of ozone?

19. ____________

20. How many grams is 2.5 mol of the diatomic form of oxygen? 20. ____________

21. How many kilograms is 2.5 mol of ozone? 21. ____________

22. Describe the differences between an ideal gas and a real gas. ____________

____

____________.

Name ______________________________

IB Physics

Commack High School

Teacher ____________________

Thermal Physics, Thermodynamics and Option B: Engineering Physics

(for the curriculum changes *as of 2016*)

Contents Page:

Aaron Mizrahi Calvin Lui

Thermal Physics Project (edited a bit)

Thermal Concepts 3.2 Outline:

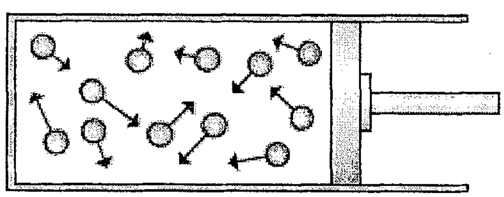
Preface: This is **not** the most basic information required for the Thermal Component of Physics. It is expected that you have read some of these more fundamental concepts. You can receive the prerequisite packet from your teacher. This Outline intends to compile the information that you are expected to know for the I.B. exam and provide some practice questions. This is **not** intended to replace any study materials (textbook or study guide) for the unit.

Assumptions of an Ideal Gas

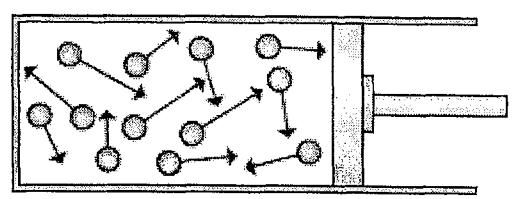
- The molecules are perfectly elastic
- The molecules are identical spheres
- There are no forces between molecules, except during collisions (therefore, in between collisions, velocity of molecules is constant)
- Volume of molecule is very small compared to total volume of gas

$$KE_{ave} \propto T$$

$$Higher\ Temperature \rightarrow Higher\ Particle\ Velocity \rightarrow Higher\ Average\ KE$$



low temperature, small average KE



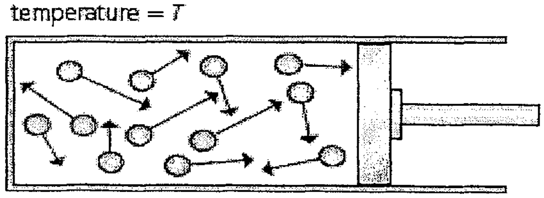
high temperature, large average KE

For two substances at the same temperature (T):

$$\frac{1}{2} m_A v_A^2 = \frac{1}{2} m_B v_B^2$$

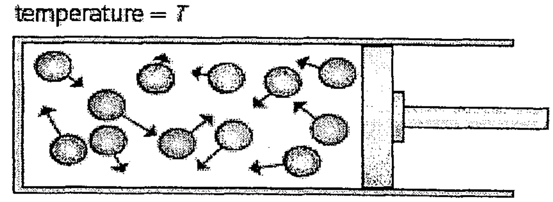
$$\frac{m_A}{m_B} = \frac{v_B^2}{v_A^2}$$

temperature = T



small molecules, high velocity

temperature = T



large molecules, low velocity

$$Pressure = \frac{Force}{Area}$$

F in x = $\frac{\Delta p}{\Delta t} = \frac{m*2v}{t} = \frac{2mv}{(\frac{2L}{v})} = \frac{mv^2}{L} = \frac{dp}{dt}$ $(calculus)$ (see page 7)

F in x /Area $= \frac{mv^2}{L} / Area = \frac{mv^2}{Area*L} = \frac{mv^2}{Volume}$

P in x *Volume = mv^2

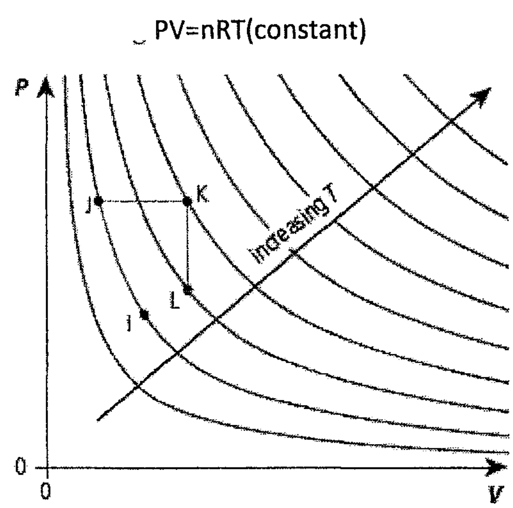
P *Volume is proportional to KE

P *Volume is proportional to T

This is the ideal gas law!!!

Boyle's Law (constant Temperature $P \propto V^{-1}$

Graphical representation of Boyle's law



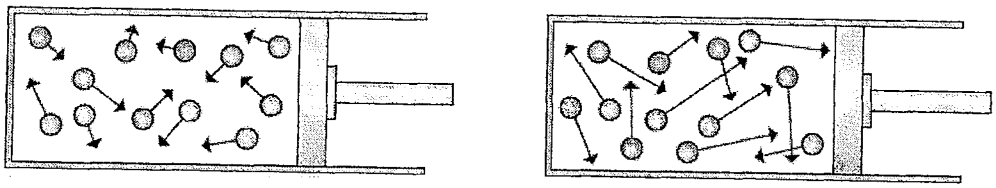
(as distance from origin increases, levels of constant temperature are higher)

IJ – constant temperature (isothermal)

JK - constant pressure (isobaric)

KL – constant volume (isochoric)

Pressure Law (constant volume): $P \propto T$



If temperature increases, average KE increases. Change in momentum increases because molecules collide with wall more often and Δv increases. According to Newton's Second Law,

$$\text{Force exerted} = \text{Rate of change of momentum} = \frac{\Delta p}{\Delta t} = \frac{mv^2}{L} = \frac{dp}{dt}\,(calculus)$$

As a result, the force on the wall is increased. Hence the pressure increases ($P = \frac{F}{A}$).

Graphical Representation of Pressure Law

$$\frac{P}{T} = \frac{nR}{V}\,(constant)$$

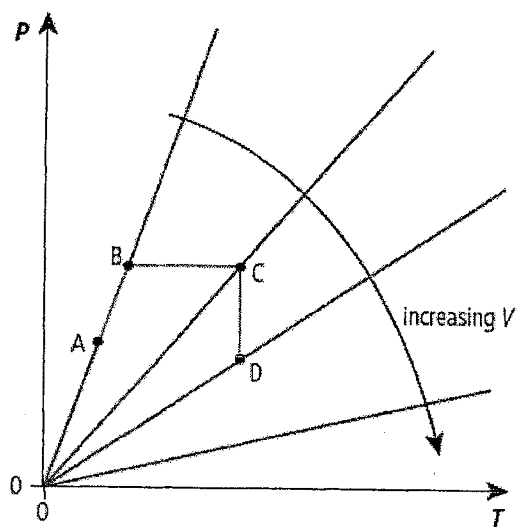


Figure 3.50 *P* vs *T* for different *V*.

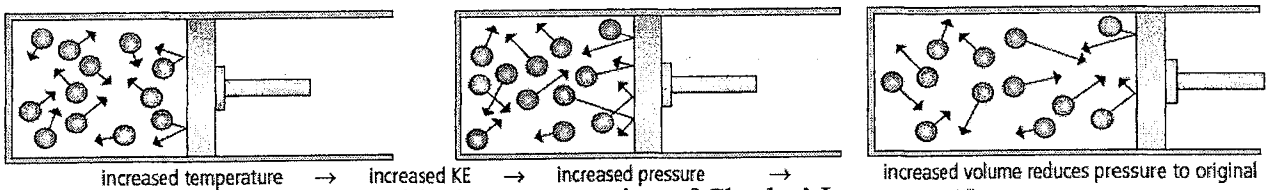
CD – constant temperature (isothermal)

BC - constant pressure (isobaric)

AB – constant volume (isochoric)

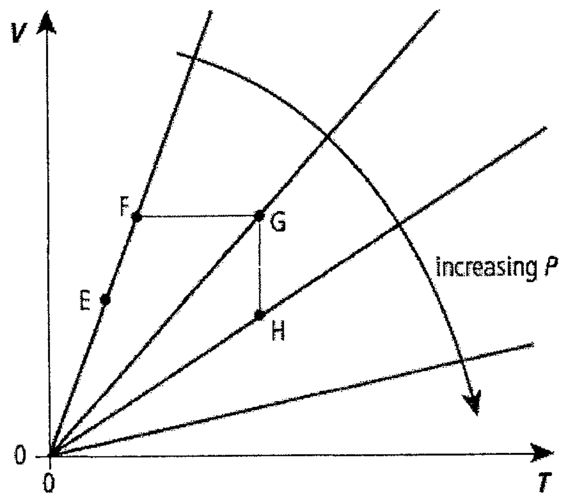
Charles' Law (constant pressure): $V \propto T$

As the temperature of a gas is increased the molecules move faster causing an increase in pressure. However, if the volume is increased in proportion to the increase in temperature the pressure will remain the same. This is shown in Figure 3.51.



Graphical Representation of Charles' Law

$$\frac{V}{T} = \frac{nR}{P}\text{(constant)}$$

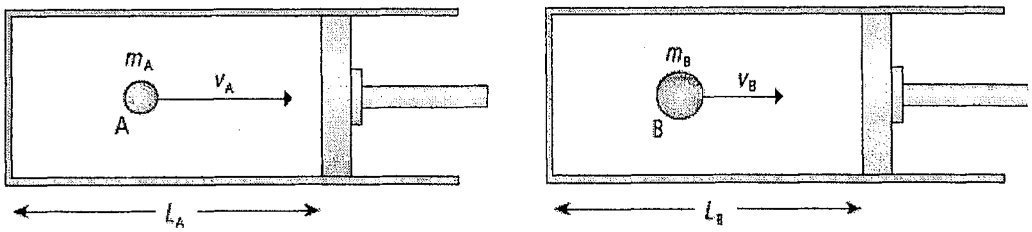


EF – constant pressure (isobaric)

FG – constant volume (isochoric)

GH – constant temperature (isothermal)

Avogadro's hypothesis: Two equal volumes of gas have the same number of molecules if $P_1 = P_2$ and $T_1 = T_2$. PV=nRT



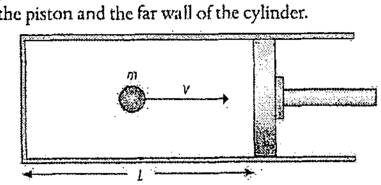
The force exerted by each molecule is given by $\frac{mv^2}{L} = \frac{2KE}{L}$ (see page 114).

Both gases have the same KE so:

$$\text{force exerted by A} = \frac{2KE}{L_A}$$
$$\text{force exerted by B} = \frac{2KE}{L_B}$$

Page 114:

To understand how the pressure is related to the motion of the molecules we can consider the simplified version shown in Figure 3.41 where one molecule is bouncing rapidly between the piston and the far wall of the cylinder.



When the molecule hits the piston it bounces off elastically. The magnitude of change in momentum is therefore $2mv$. The force exerted on the piston is equal to the rate of change of momentum which in this case = change in momentum × rate of hitting the wall. The rate at which the molecule hits the wall depends on how long it takes for the molecule to travel to the other end of the cylinder and back:

$$\text{time for molecule to travel to other end and back} = \frac{2L}{v}$$

$$\text{number of hits per unit time} = \frac{1}{\left(\frac{2L}{v}\right)} = \frac{v}{2L}$$

$$\text{rate of change of momentum} = 2mv \times \frac{v}{2L} = \frac{mv^2}{L}$$

so the pressure is directly related to the KE of the particles and therefore the temperature of the gas.

Ideal Gas Law

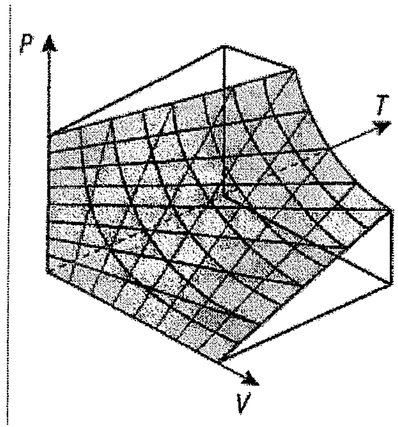
$$PV = nRT$$

n = number of moles of gas

$R = 8.31\ J\ mol^{-1}\ k^{-1}$

Graphical representation of the ideal gas equation

This relationship can be represented on a graph with three axes as in Figure 3.56. The shaded area represents all the possible states of a fixed mass of gas. No matter what you do to the gas, its *P*, *V*, and *T* will always be on this surface. This is quite difficult to draw so the 2-dimensional views shown before are used instead.



Following this section is a selection of questions such that you may apply the compiled information in this outline. While this guide highlights some of the most important details of the chapter, we recommend that you read any corresponding sections in your textbook and studyguide. In other words, this guide is meant to supplement what you have read not substitute it.

Exercises

19 The pressure of 10 m^3 of gas in a sealed container at 300 K is 250 kPa. If the temperature of the gas is changed to 350 K, what will the pressure be?

20 A container of volume 2 m^3 contains 5 moles of gas. If the temperature of the gas is 293 K:

(a) what is the pressure exerted by the gas?
(b) what is the new pressure if half of the gas leaks out?

21 A piston contains 250 cm^3 of gas at 300 K and a pressure of 150 kPa. The gas expands, causing the pressure to go down to 100 kPa and the temperature drops to 250 K. What is the new volume?

22 A sample of gas trapped in a piston is heated and compressed at the same time. This results in a doubling of temperature and a halving of the volume. If the initial pressure was 100 kPa, what will the final pressure be?

3. This question is about modelling the thermal processes involved when a person is running. When running, a person generates *thermal energy* but maintains approximately constant temperature.

(a) Explain what *thermal energy* and *temperature* mean. Distinguish between the two concepts. (4)

The following simple model may be used to estimate the rise in temperature of a runner assuming no thermal energy is lost.
A closed container holds 70 kg of water, representing the mass of the runner. The water is heated at a rate of 1200 W for 30 minutes. This represents the energy generation in the runner.

(b) (i) Show that the thermal energy generated by the heater is 2.2×10^6 J. (2)

(ii) Calculate the temperature rise of the water, assuming no energy losses from the water. The specific heat capacity of water is 4200 J kg^{-1} K^{-1}. (3)

(c) The temperature rise calculated in (b) would be dangerous for the runner. Outline **three** mechanisms, other than evaporation, by which the container in the model would transfer energy to its surroundings. (6)

A further process by which energy is lost from the runner is the evaporation of sweat.

(d) (i) Describe, in terms of molecular behaviour, why evaporation causes cooling. (3)

(ii) Percentage of generated energy lost by sweating: 50%

Specific latent heat of vaporization of sweat: 2.26×10^6 J kg^{-1}

Using the information above, and your answer to (b) (i), estimate the mass of sweat evaporated from the runner. (3)

(iii) State and explain two factors that affect the rate of evaporation of sweat from the skin of the runner. (4)

5. This question is about ideal gases.

(a) The atoms or molecules of an ideal gas are assumed to be identical hard elastic spheres that have negligible volume compared with the volume of the containing vessel.

(i) State **two** further assumptions of the kinetic theory of an ideal gas. (2)

(ii) Suggest why only the average kinetic energy of the molecules of an ideal gas is related to the internal energy of the gas. (3)

(b) An ideal gas is contained in a cylinder by means of a frictionless piston.

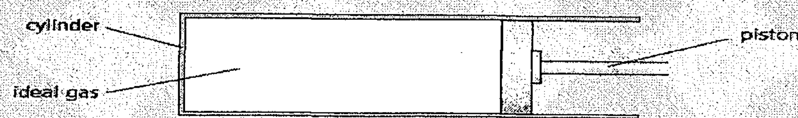


Figure 3.59.

At temperature 290 K and pressure 4.8×10^5 Pa, the gas has volume 9.2×10^{-4} m³.

(i) Calculate the number of moles of the gas. (2)

(ii) The gas is compressed isothermally to a volume of 2.3×10^{-4} m³. Determine the pressure P of the gas. (2)

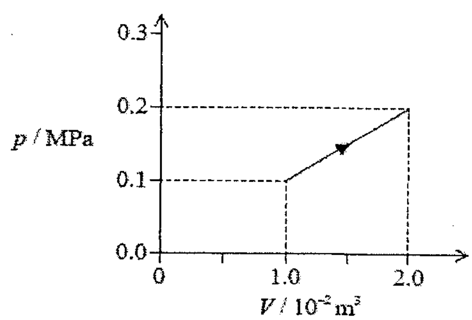
(iii) The gas is now heated at constant volume to a temperature of 420 K. Show that the pressure of the gas is now 2.8×10^6 Pa. (1)

(c) The gas in (b)(iii) is now expanded adiabatically so that its temperature and pressure return to 290 K and 4.8×10^5 Pa respectively. This state is shown in Figure 3.60 as point A.

Figure 3.60.

(i) Copy Figure 3.60 and on the axes sketch a pressure–volume (P–V) diagram for the changes in (b)(ii), (b)(iii), and (c). (3)

12. The graph shows the variation with volume V of the pressure p of a fixed mass of an ideal gas as the temperature of the gas is raised.



What is the work done by the gas during the process?

A. 0.5kJ

B. 1.0kJ

C. 1.5kJ

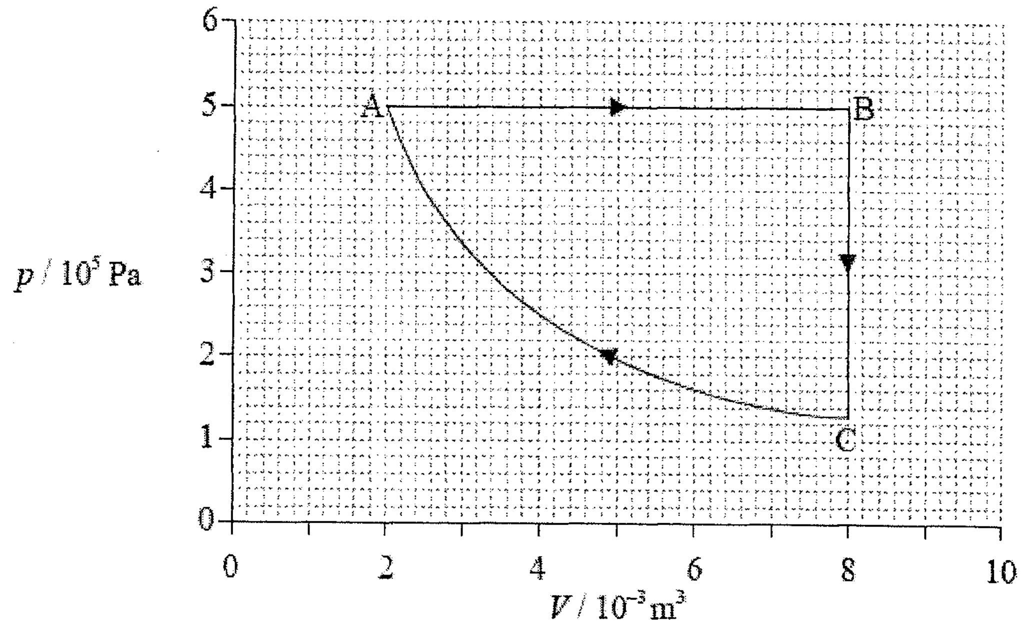
D. 2.0kJ

CHALLENGE YOURSELF

1 Two identical flasks each full of air are connected by a thin tube on a day when the temperature is 300 K and the atmospheric pressure 100 kPa. One of the flasks is then heated to 400 K while the other one is kept at 300 K. What is the new pressure in the flasks?

(Option B continued)

7. The pressure volume (pV) diagram shows a cycle ABCA of a heat engine. The working substance of the engine is a fixed mass of an ideal gas.



The temperature of the gas at A is 400 K.

(a) Calculate the maximum temperature of the gas during the cycle. *[1]*

. . . .

. . . .

(Option B continues on the following page)

(Option B, question 7 continued)

(b) For the isobaric expansion AB, calculate the

(i) work done by the gas. *[2]*

. . . .
. . . .
. . . .
. . . .

(ii) change in the internal energy of the gas. *[1]*

. . . .
. . . .
. . . .
. . . .

(iii) thermal energy transferred to the gas. *[1]*

. . . .
. . . .
. . . .
. . . .

(Option B, question 7 continued)

(c) The work done on the gas during the isothermal compression is 1390 J. Determine the change in entropy of the gas for this compression. *[2]*

. . . .

. . . .

. . . .

. . . .

(d) Determine the efficiency of the cycle ABCA. *[2]*

. . . .

. . . .

. . . .

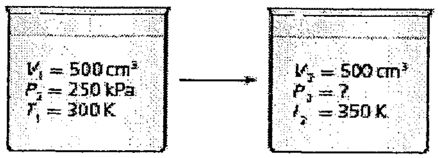
. . . .

(e) State whether the efficiency of a Carnot engine operating between the same temperatures as those operating in cycle ABCA on page 14, would be greater than, equal to, **or** less than the efficiency in (d). *[1]*

. . . .

Solutions:

19

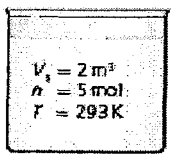


$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\frac{250 \times 500}{300} = \frac{P_2 \times 500}{350}$$

$$P_2 = \frac{250 \times 350}{300} = 292\,kPa$$

20



(a) $PV = nRT$

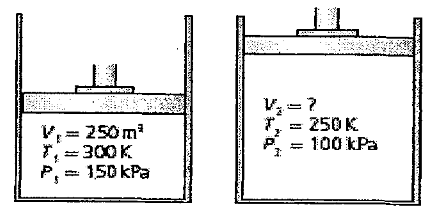
$$P = \frac{nRT}{V} = \frac{5 \times 8.31 \times 293}{2}$$

$P = 6\,kPa$

(b) If half of gas leaks, $n = 2.5$ mol

$P = 3\,kPa$

21

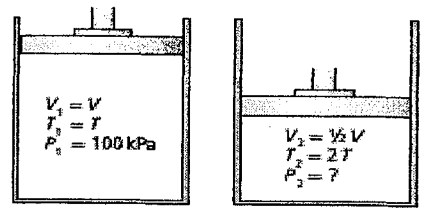


$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \Rightarrow \frac{150 \times 250}{300} = \frac{100 \times V_2}{250}$$

$$V_2 = \frac{150 \times 250 \times 250}{300 \times 100}$$

$V_2 = 312.5\,cm^3$

22



$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \Rightarrow \frac{100 \times V}{T} = \frac{P_2 \times ½V}{2T}$$

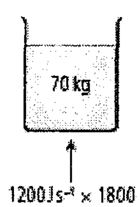
$$P_2 = \frac{2 \times 100}{½} = 400\,kPa$$

3 (a) In this context thermal energy is the internal energy of the molecules of the runner. This can be KE and PE. Increased thermal energy will increase the average KE of the molecules which increases the temperature, in other words the runner becomes hot.

(b) (i) Energy generated = power × time
= 1200 × 3600 = 2.2 × 10^6 J

(ii) $Q = mc\Delta\theta$

$$\Delta\theta = \frac{Q}{mc} = \frac{2.2 \times 10^6}{70 \times 4200} = 7.5\,K$$



(c) *Convection*
Conduction
Radiation This is no longer on the syllabus.

(d) (i) The molecules with greatest KE leave the surface resulting in a decrease in average KE and hence temperature.

(ii) Total energy generated = 2.2 × 10^6 J
50% lost in evaporation = 1.1 × 10^6 J
This energy goes to latent heat of vaporization $Q = mL$

$$m = \frac{Q}{L} = \frac{1.1 \times 10^6}{2.26 \times 10^6} = 487\,g$$

(iii) Wind
Skin temperature
Humidity
Air temperature
Area of skin
Clothing

5

(ii) The molecules of an ideal gas have no forces between them so changing their position does not require work to be done; gas molecules therefore have no PE; this implies that the internal energy of a gas is related to the average KE of the molecules. If energy is added to the gas, temperature increases so we see that temperature is related to the average KE.

(b) (i) Using $PV = nRT$

$T = 290\text{K}$

$P = 4.8 \times 10^5\text{Pa}$

$V = 9.2 \times 10^{-4}\text{m}^3$

$n = \frac{PV}{RT} = \frac{4.8 \times 10^5 \times 9.2 \times 10^{-4}}{8.3 \times 290}$

$= 0.18$ mol

(ii) If temperature constant $P_1V_1 = P_2V_2$

$4.8 \times 10^5 \times 9.2 \times 10^{-4} = P_2 \times 2.3 \times 10^{-4}$

$P_2 = \left(\frac{9.2}{2.3}\right) \times 4.8 \times 10^5 = 19 \times 10^5$ Pa

(iii) If volume is constant $\frac{P_1}{T_1} = \frac{P_2}{T_2}$

$P_1 = 19 \times 10^5\text{Pa}$

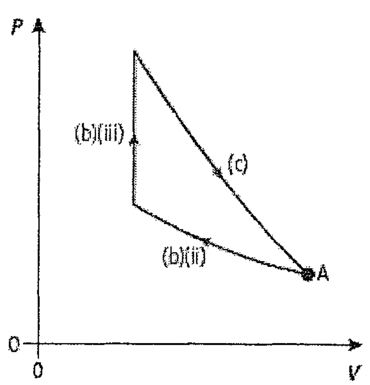
$T_1 = 290\text{K}$

$P_2 = ?$

$T_2 = 420\text{K}$

$P_2 = 19 \times 10^5 \times \frac{420}{290} = 2.8 \times 10^6\text{Pa}$

(c)

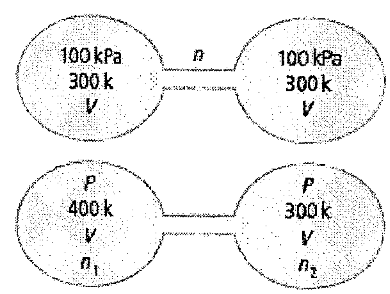


5 (a) (i) The molecules of an ideal gas are considered to be small perfectly elastic spheres moving in random motion with no forces between them. Small and elastic is mentioned in the question so

1. Motion is random
2. No forces between molecules except when colliding

Challenge yourself

1



When first filled and joined we can treat the two flasks as one container. Applying the ideal gas equation, $PV = nRT$, we get $100 \times 2V = nR \times 300$

After one flask is heated we have to treat them separately but since they are connected the pressure is the same.

$PV = n_1R \times 400$

$PV = n_2R \times 300$

The total number of moles n is the same before and after so

$n = n_1 + n_2$

substituting gives $\frac{200V}{300R} = \frac{PV}{400R} + \frac{PV}{300R}$

$\frac{2}{3} = \left(\frac{1}{400} + \frac{1}{300}\right)P$

$P = 114.3\text{kPa}$

Question 12:

Work= area under curve F=pA, container moves x distance as a result of force, W=pAx, Ax also = V, W=pV

= area of triangular component + area of square rectanglular component (be careful with units)

= .5(0.1MPa x $1\times10^{-2}m^3$) + (0.1MPa x $1\times10^{-2}m^3$)= 1.5kJ

Question			Answers	Notes	Total
7.	a		$\langle$ maximum is at B and so $T_B = 400\times\frac{8}{2} = \rangle 1600 \langle K \rangle$ ✓		1
	b	i	$W = \langle p\Delta V = \rangle 5.0\times10^5 \times[8.0-2.0]\times10^{-3}$ ✓ $W = 3.0\times10^3 \langle J \rangle$ ✓	*Award [2] for a bald correct answer.*	2
	b	ii	$\Delta U = \langle \frac{3}{2}p\Delta V = \frac{3}{2}\times3.0\times10^3 = \rangle 4.5\times10^3 \langle J \rangle$ ✓	*Award [1] for a bald correct answer.*	1
	b	iii	$Q = \langle \Delta U + W = 3.0\times10^3 + 4.5\times10^3 = \rangle 7.5\times10^3 \langle J \rangle$ ✓	*Award [1] for a bald correct answer.*	1
	c		$\Delta S = \frac{Q}{T} = -\frac{1390}{400}$ ✓ $\Delta S = -3.48 \approx -3.5 \langle JK^{-1} \rangle$ ✓	*Award [1 max] for omitted minus sign.* *Award [2] for a bald correct answer.*	2
	d		$e = \frac{3000-1390}{7500}$ ✓ $e = 0.21$ ✓	*Award [2] for a bald correct answer.*	2
	e		greater ✓		1

Thermodynamics 10.2/B.2 Outline:

$$Average\ KE = \frac{3}{2}kT$$

$$k = Bolzmann's\ Constant = 1.38 \times 10^{-23} JK^{-1}$$

$$T = Temperature$$

$$Total\ KE = \frac{3}{2}N_A kT$$

$$N_A k = Universal\ Gas\ Constant = 8.31\, J\ mol^{-1}K^{-1}$$

$$Internal\ Energy = U = 1.5nRT$$

$$Heat = Q = \Delta U$$

<u>Work Done by a Gas</u>

Work is done when the point of application of a force moves in the direction of the force. If the pressure of a gas pushes a piston out, then the force exerted on the piston is moving in the direction of the force, so work is done. The example in Figure 10.41 is of a gas expanding at constant pressure. In this case, the force exerted on the piston = $P \times A$. The work done when the piston moved distance Δd is therefore given by:

Work done = $P \times A \times \Delta d$

but $A\Delta d$ is the change in volume ΔV, so

Work done = $P\Delta V$

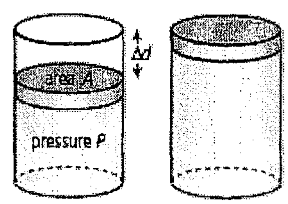
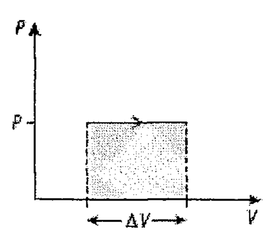


Figure 10.42 is the P–V graph for this constant pressure expansion. From this we can see that the work done is given by the area under the graph. This is true for all processes.



Consider $Work = Fd\ cos\theta$ In the above example, with the force moving in the direction of the application of the force, $\theta = 0°$ thus $cos\theta = 1$.

<u>The First Law of Thermodynamics</u>

Increasing volume implies that work is being done by the gas.

Decreasing volume implies that work is being done on the gas.

Temperature is directly related to internal energy (U).

According to the law of conservation of energy, energy can neither be created nor destroyed, so the amount of heat, Q, added to a gas must equal the work done by the gas, W, plus the increase in internal energy, ΔU. This is so fundamental to the way physical systems behave that it is called the *first law of thermodynamics*. This can be written in the following way:

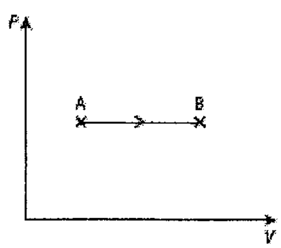
$$Q = \Delta U + W$$

This would be nice and easy if the only thing a gas could do is gain heat, get hot, and do work. However, heat can be added and lost, work can be done by the gas and on the gas, and the internal energy can increase and decrease. To help us understand all the different possibilities, we will use the P–V diagram to represent the states of a gas.

Using *P–V* diagrams in thermodynamics

We have seen how a P–V diagram enables us to see the changes in P, V, and T that take place when a gas changes from one state to another. It also tells us what energy changes are taking place. If we consider the transformation represented in Figure 10.43 we can deduce that when the gas changes from A to B:

1 since the volume is increasing, the gas is doing work (W is positive).
2 since the temperature is increasing, the internal energy is increasing (ΔU is positive).



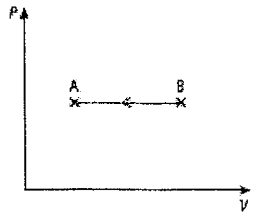
If we then apply the first law $Q = \Delta U + W$ we can conclude that if both ΔU and W are positive then Q must also be positive, so heat must have been added.

This is a typical example of how we use the *P–V* diagram with the first law: we use the diagram to find out how the temperature changes and whether work is done *by* the gas or *on* the gas, and then use the first law to deduce whether heat is added or lost.

Constant pressure compression (isobaric)

The previous example was an expansion at constant pressure. Now we will consider the constant pressure (isobaric) compression shown in Figure 10.44.

1 Temperature decrease implies that the internal energy decreases (ΔU = negative).
2 Volume decrease implies that work is done on the gas (W = negative).



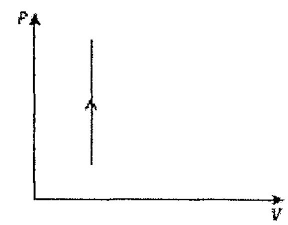
Applying the first law, $Q = \Delta U + W$, tells us that Q is also negative, so heat is lost.

Constant volume increase in temperature (isochoric)

Figure 10.45 is the P–V graph for a gas undergoing a constant volume transformation. From the graph we can deduce that:

1. The volume isn't changing, so no work is done ($W = 0$).
2. The gas changes to a higher isotherm so the temperature is increasing; this means that the internal energy is increasing (ΔU = positive).

Applying the first law $Q = \Delta U + W$ we can conclude that $Q = \Delta U$ so if ΔU is positive then Q is also positive – heat has been added.



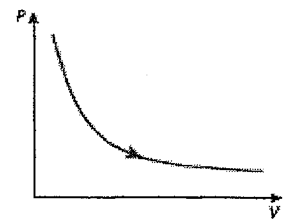
Graph A

Isothermal expansion

For an ideal gas $PV = nRT$ so if the temperature is constant P–V = constant which implies that $P = \frac{\text{const}}{V}$ so the P–V graph follows the curve shown in Figure 10.46 ($y = \frac{k}{x}$).

From this P–V diagram we can deduce that:

1. the temperature doesn't change so there is no change in internal energy ($\Delta U = 0$)
2. the volume increases so work is done by the gas (W = positive).



Graph B

Applying the first law, $Q = \Delta U + W$, we conclude that $Q = W$ so heat must have been added. The heat added enables the gas to do work.

Graph A: Consider that at constant volume, pressure and temperature are directly proportional

Graph B: Consider that when pressure and volume are inversely proportional, temperature is constant

Adiabatic expansion

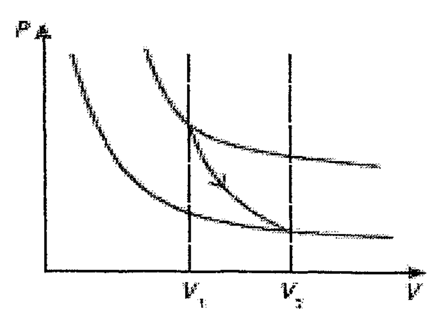
An adiabatic process is when there is no exchange of heat between the system and the surroundings. To understand how this will be on a P–V graph let us compare an adiabatic expansion with an isothermal expansion between the same two volumes.

During an isothermal expansion work is done by the gas and the internal energy stays constant so heat must have been added. To do the same amount of work without adding heat the internal energy must go down resulting in a reduction in temperature leading to the curve in Figure 10.47.

It can be shown that for an adiabatic transformation PV^{γ} = constant so the shape of this curve is $y = \frac{1}{x^{\gamma}}$.

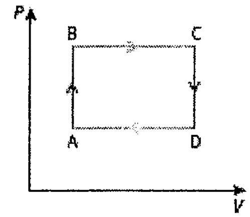
From the P–V diagram we can deduce that:

1. the volume is increased so work is done by the gas (W = positive).
2. the temperature decreases so the internal energy is reduced (ΔU = negative).



Cyclic processes

A cyclic process is a series of transformations that take a gas back to its original state. When represented on a P–V diagram they form a closed loop such as the one shown in Figure 10.54.



In this example the cycle is clockwise so the sequence of transformations is:

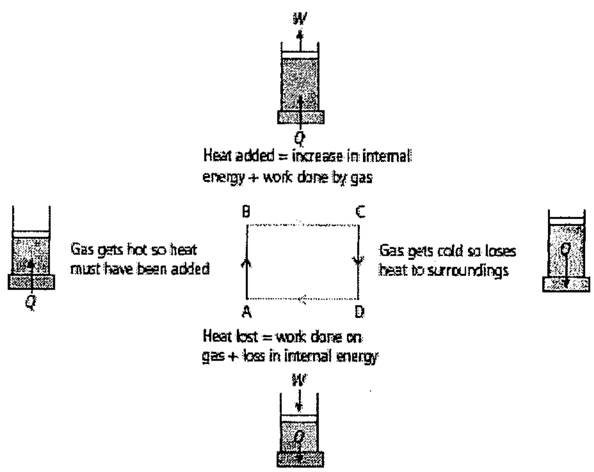
A–B isochoric temperature rise

B–C isobaric expansion

C–D isochoric temperature drop

D–A isobaric compression.

In the process of completing this cycle, work is done on the gas from D to A and the gas does work from B to C. It is clear from the diagram that the work done by the gas is greater than the work done on the gas (since the area under the graph is greater from B to C than from D to A) so net work is done. What we have here is an engine; heat is added and work is done. Let us look at this cycle more closely.



The secret to the operation of all heat engines is that the gas is cooled down before it is compressed back to its original volume. The cold gas is easier to compress than a hot one so when the gas is hot it does work, but it's reset when it's cold.

The balloon engine from Chapter 8 operates on the same principle; when the gas is hot the balloon goes up, doing work. The balloon is then allowed to cool so that pulling it down does not use as much energy as was gained when it went up.

Energy flow diagram

The principle of a heat engine can be represented by an energy flow diagram as in Figure 10.56. Heat flows from a hot source to a cold one through the engine which converts some of it into work.

The *thermal efficiency* η of an engine is defined as the ratio of the work it does to the amount of heat energy put in:

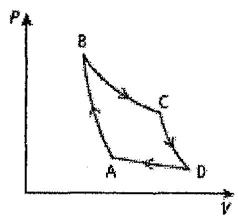
$$\eta = \frac{W}{Q_H}$$

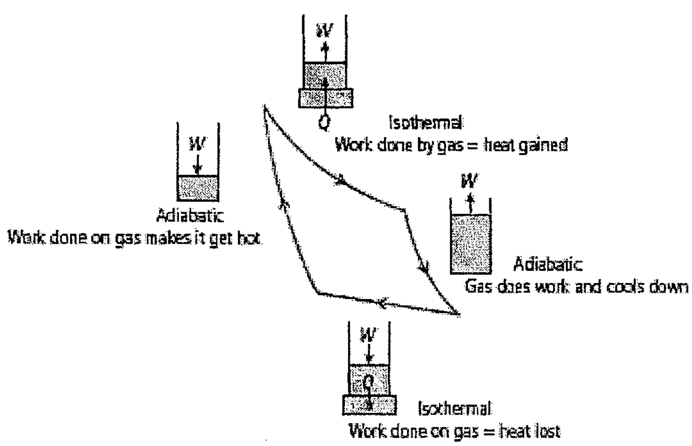
but $W = Q_H - Q_C$ so:

$$\eta = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{Q_C}{Q_H}$$

The Carnot cycle

When heat is added in the previous example the source of heat is much hotter than the gas. A more efficient process would be to transfer heat at the same temperature as the gas. The most efficient cycle possible is the Carnot cycle as represented in Figure 10.57. As Figure 10.57 shows, this consists of two isothermal transformations when heat is transferred at the same temperature as the surroundings and two adiabatic processes when the volume is changed, resulting in a change in temperature without exchanging heat to the surroundings. This is an idealized process that would have to take place very slowly but sets the limit on what is possible.





The amount of heat transferred in and out of the gas during the isothermal processes is directly proportional to the temperature in kelvin, so:

$$Q_H \propto T_H \text{ and } Q_C \propto T_C$$

The efficiency of a Carnot cycle is therefore:

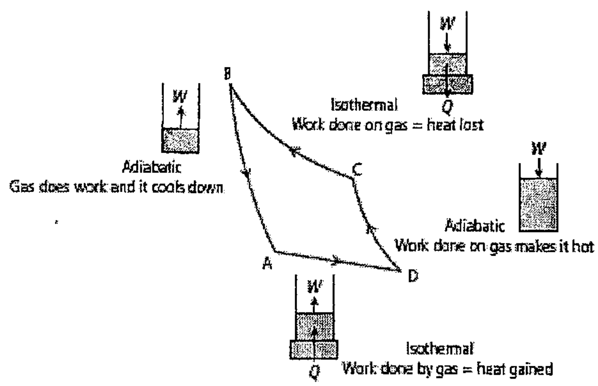
$$\eta = 1 - \frac{Q_C}{Q_H} = 1 - \frac{T_C}{T_H}$$

No engine can have a higher efficiency than this.

We can see that the efficiency depends on the difference between the temperatures of the hot and cold parts of the cycle. If the cold part was absolute zero (0 K) then no work would have to be done to push back the piston and the efficiency would be 1.

The reverse cycle

Let us consider what would happen if the Carnot cycle was operated in reverse. The details of this are shown in Figure 10.59.



The interesting thing about this cycle is that heat is lost to the hot body during the isothermal compression (C to B) and gained from the cold body during the isothermal expansion (A to D). So heat has been taken from something cold and given to something hot. This is what a refrigerator does – it takes heat from the cold food inside and gives it to the warm room. To make this possible, work must be done on the gas (D to C) so that it gets hot enough to give heat to the hot body.

The second law of thermodynamics

We have seen that we can use our simple thermodynamic system of a cylinder of gas to convert heat into work but to do this we must transfer heat from a hot body to a cold one. This means that we will always lose some heat. It would be even better if we could take a source of heat and transfer all the energy to work without losing any to a cold body. According to the first law of thermodynamics this should be possible since energy would be conserved. However, it can't be done. The reason for this is fundamental to the way matter behaves. To understand why, let us first consider a seemingly unconnected example in which a gas is pumped into a container as in Figure 10.62. The molecules of gas flow into the container in a nice orderly fashion through a small opening, all travelling in the same direction with the same speed (not really possible but this is a thought experiment). The molecules travel across the container and hit the other side at which point things start to get messy. The molecules hit each other; they no longer have the same energy and direction but move about in random motion, some moving fast and others moving slowly, just like the way we know the molecules of gas behave. No matter how long we wait, the molecules will never line up with the same speed again (at least it is extremely unlikely) even though, according to the law of conservation of energy, this would be perfectly OK.

Just as physical systems tend to a position of lowest potential energy, they also tend to a state where the energy is most disordered. When a metal block is held above the ground each molecule has approximately the same amount of potential energy but when it is dropped onto the floor that energy goes to increase the kinetic and potential energy of the molecules of the block and ground. Those molecules interact with neighbouring molecules as the energy is spread out. This energy will never collect together again to allow the block to return to its original position.

So an engine that, for example, took heat energy from the random motion of molecules in the air and converted it all to work to lift a mass from the ground would be creating an ordered form of energy (the PE of the mass) out of the random spread of energy in the air and that is not possible. However, if some of the energy was put into a cold body the net effect could be a more disordered form of energy overall, so this could be possible.

The second law of thermodynamics states this in a concise way:

It is not possible for a heat engine working in a cycle to absorb thermal energy and convert it all to work.

This is the Kelvin–Planck statement of the law.

Entropy

The second law of thermodynamics is about the spreading out of energy. This can be quantified by using the quantity *entropy*.

The change of entropy is ΔS, when a quantity of heat flow into a body at temperature T is equal to $\frac{Q}{T}$.

$$\Delta S = \frac{Q}{T}$$

The unit of entropy is $J\,K^{-1}$.

For example, consider the situation of a 1 kg block of ice melting in a room that is at a constant temperature 300 K. To melt the block of ice, it must gain 3.35×10^5 J of energy. Ice melts at a constant 273 K so:

The gain in entropy of the ice $= \frac{3.35 \times 10^5}{273} = 1.23 \times 10^3\,J\,K^{-1}$

The loss of entropy by the room $= \frac{3.35 \times 10^5}{300} = 1.12 \times 10^3\,J\,K^{-1}$

We can see from this that the entropy has increased.

Entropy always increases in any transfer of heat since heat always flows from hot bodies to cold bodies. We can therefore rewrite the second law in terms of entropy.

In any cyclic process the entropy will either stay the same or increase.

Entropy is a measure of how spread out or disordered the energy has become. Saying entropy has increased implies that the energy has become more spread out.

This statement also implies that heat cannot spontaneously flow from a cold object to a hot object. We have seen that this is possible by reversing the cycle of a heat engine but then work must be done. A third way of stating the second law is therefore:

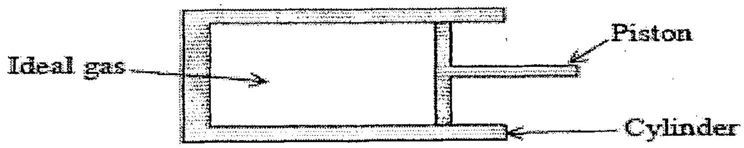
It is not possible for heat to be transferred from a cold body to a warmer one without work being done.

This is the Clausius statement of the law.

Following this outline is a selection of old I.B. questions related to the compiled subjects. We recommend going through section 10.2 of the physics textbook and completing the corresponding questions first. Additionally, it may be helpful to read this section in the study guide for more information. Realize that this is a small selection of questions related to Thermal Physics and that many old exams are available with more questions and their mark schemes.

(Question B continued)

A sample of an ideal gas is contained in a cylinder fitted with a piston, as shown below.



(d) (i) Explain, in terms of molecules, what is meant by the internal energy of the gas. [ ]

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(ii) The piston is suddenly moved inwards, decreasing the volume of the gas. By considering the speeds of molecules, suggest why the temperature of the gas changes. [5]

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(iii) The gas now expands at constant pressure p so that the volume increases by an amount V. Derive an expression for the work done by the gas. [4]

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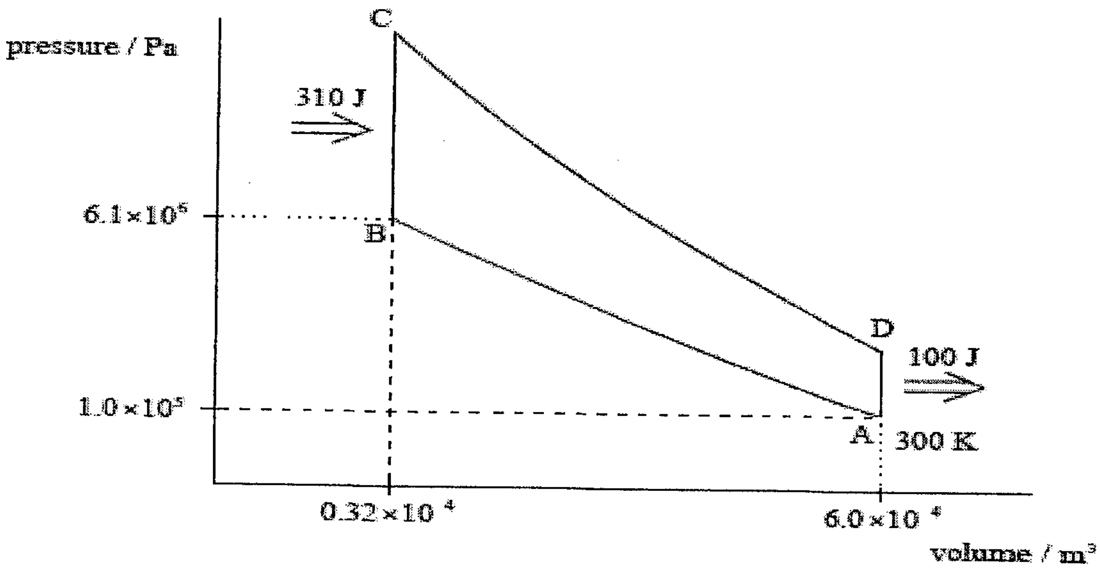
(This question continues on the following page)

(Question B continued)

An engine operates by using an isolated mass of an ideal gas. The gas is compressed adiabatically and then it is heated at constant volume. The gas gains 310 J of energy during the heating process. The gas then expands adiabatically. Finally, the gas is cooled so that it returns to its original state. During the cooling process, 100 J of energy is extracted. The cycle is shown below.



(e) (i) Mark, on the diagram, arrows to show the direction of operation of the stages of the cycle. [1]

(ii) Using data for point A, calculate the number of moles of gas. [1]

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(iii) Determine the temperature of the gas at point B in the cycle. [1]

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(This question continues on the following page)

B4. This question is in two parts. **Part 1** is about gases and specific heat capacity and **Part 2** is about gravitation.

Part 1 Gases and specific heat capacity

(a) State what is meant by an *ideal* gas. *[2]*

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An ideal gas occupies a volume of $1.2\,\text{m}^3$ at a temperature of $27\,^\circ\text{C}$ and a pressure of 1.0×10^5 Pa. The density of the gas is $1.6\,\text{kg}\,\text{m}^{-3}$. It is found that 1.5×10^4 J of energy is required to raise the temperature of the gas to $52\,^\circ\text{C}$ when the gas is held at constant volume.

(b) Determine the specific heat capacity at constant volume of the gas. *[3]*

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(c) A second sample of the same gas as above is heated from $27\,^\circ\text{C}$ to $52\,^\circ\text{C}$ at constant pressure.

(i) Show that the volume of the gas at $52\,^\circ\text{C}$ is $1.3\,\text{m}^3$. *[2]*

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(ii) Calculate the work done by the gas during the heating process. *[2]*

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(d) The specific heat capacity for the gas kept at constant volume is different to that when the gas is kept at constant pressure. State and explain whether the specific heat capacity for an ideal gas at constant pressure is greater or less than the specific heat capacity of the gas at constant volume. *[3]*

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(This question continues on the following page)

A3. This question is about entropy changes.

(a) State what is meant by an *increase in entropy* of a system. *[1]*

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(b) State, in terms of entropy, the second law of thermodynamics. *[2]*

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(c) When a chicken develops inside an egg, the entropy of the egg and its contents decreases. Explain how this observation is consistent with the second law of thermodynamics. *[2]*

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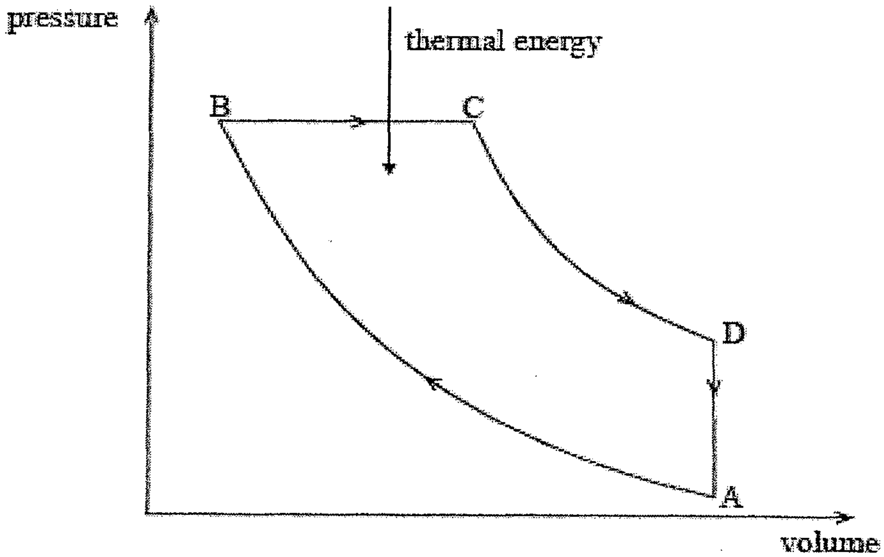
(Question B4, part 1 continued)

The diagram below shows the relation between the pressure and the volume of the air in the diesel engine for one cycle of operation of the engine. During the cycle there are two adiabatic processes, an isochoric process and an isobaric process.



(d) Explain what is meant by

(i) an adiabatic process. *[2]*

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(ii) an isochoric process. *[1]*

. . . .

. . . .

(iii) an isobaric process. *[1]*

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(Question B4, part 1 continued)

(e) Identify, from the diagram, the following processes.

(i) Adiabatic processes *[1]*

. . . .

(ii) Isochoric process *[1]*

. . . .

(iii) Isobaric process *[1]*

. . . .

During the process B $\rightarrow$ C thermal energy is absorbed.

The diesel engine has a total power output of 8.4 kW and an efficiency of 40 %. The cycle of operation is repeated 40 times every second.

(f) State what quantity is represented on the diagram by the area ABCD. *[1]*

. . . .

(g) Determine the value of the quantity that is represented by the area ABCD. *[1]*

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(h) Determine the thermal energy absorbed during the process B $\rightarrow$ C. *[2]*

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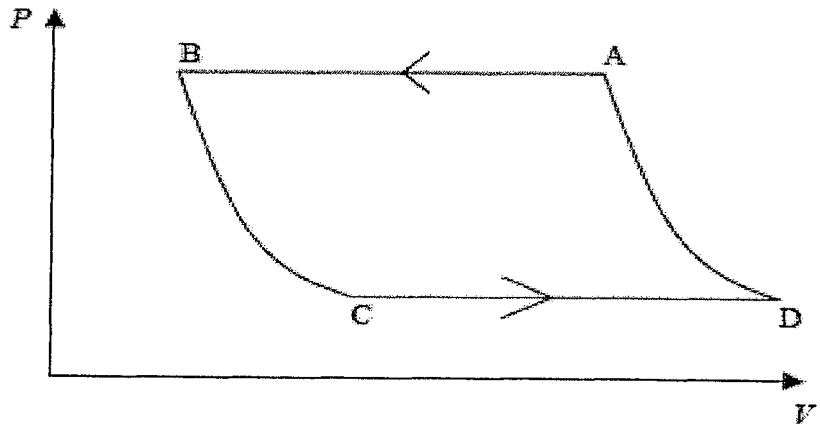
(Question A4 continued)

(b) The diagram below, shows the relation between the pressure P and the volume V of the working substance of the heat pump for one cycle of its operation.



(i) The working substance at point C of the cycle is in the liquid phase.

State the reason why both the changes from C→D and A→B are isothermal isobaric changes. *[2]*

C→D: . . . .

. . . .

A→B: . . . .

. . . .

(ii) State during which process of the cycle energy is absorbed from the cold reservoir and during which process energy is transferred to the hot reservoir. *[2]*

Energy absorbed from cold reservoir

. . . .

Energy transferred to hot reservoir

. . . .

(iii) State how the value of the work done during one cycle may be determined from the PV diagram. *[1]*

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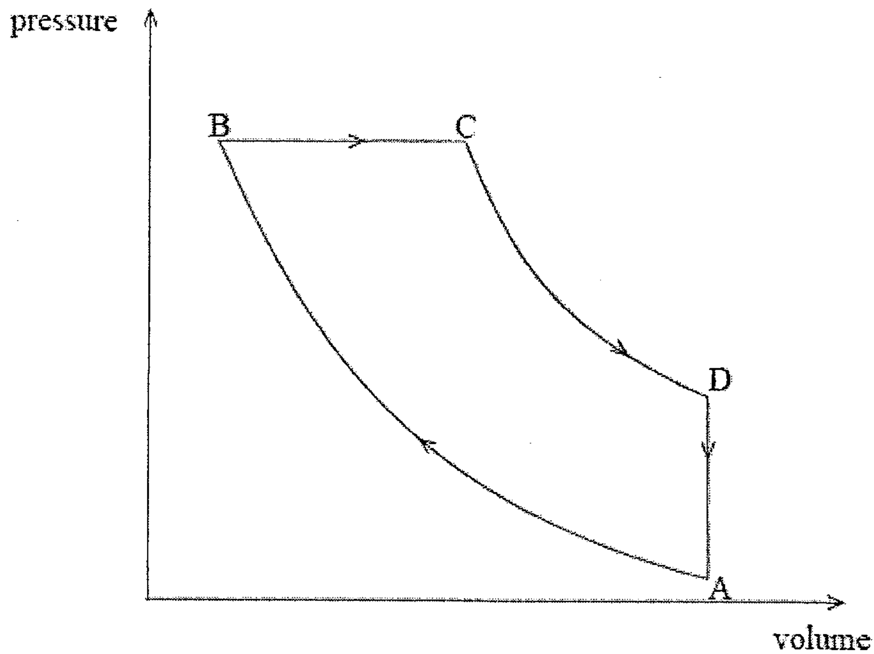
(j) The diagram below shows the relation between the pressure and the volume of the air in the engine for one cycle of operation of the engine.



(i) State the name given to the type of process represented by D→A. *[1]*

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(ii) During one cycle of the engine, the gas absorbs Q_1 units of thermal energy and Q_2 units of thermal energy are transferred from the gas. On the diagram above, draw labelled arrows to show these energy transfers. *[2]*

(iii) The efficiency of the engine is 60%. Using your answer to question (i) on page 13, calculate the values of Q_1 and Q_2. *[3]*

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Mark Schemes:

(d) (i) sum of (random) kinetic (and potential energies);
of the molecules of the system *(allow atoms or particles)*;

(ii) when a molecule strikes the piston;
rebound speed of molecule is increased;
and so <u>mean</u> kinetic energy of molecules increases;
mean kinetic energy of atoms is proportional to <u>Kelvin</u> temperature;
the temperature **rises**;
Do not allow an argument based on "less space".

(iii) force on piston = pA;
where A is area of piston. Piston moves distance x;
work done = pAx;
$Ax = \Delta V$, so $W = p\Delta V$;

– o –

(e) (i) A → B → C → D → A;

(ii) $pV = nRT$
$1.0\times10^5 \times 6\times10^{-4} = n \times 8.3 \times 300$;
$n = 0.024$ mol;

(iii) $\frac{(1.0\times10^5 \times 6\times10^{-4})}{300} = \frac{(6.1\times10^6 \times 0.32\times10^{-4})}{T}$;
$T = 976$ K;

(a) obeys the universal gas law / equation $\frac{pV}{T}$ ***or*** molecules are elastic spheres of negligible volume;
at all values of pressure, volume and temperature ***or*** no mutual force of attraction/repulsion;

(b) mass of gas $1.6\times1.2 = 1.9(2)$ kg;
use of $\Delta Q = mc\Delta\theta$;
$1.5\times10^4 = 1.92 \times c \times (52-27)$
$c = 310\,\text{J kg}^{-1}\,\text{K}^{-1}$;
Award [1] for use of density in place of mass to give 375 J kg^{-1} K^{-1} and [0] for use of volume in place of mass.

(c) (i) use of $\frac{pV}{T}$ = constant;
$V = 1.2\times\left(\frac{325}{300}\right)$;
$= 1.3\,\text{m}^3$

(ii) use of $\Delta W = p\Delta V$;
$\Delta W = 1.0\times10^5 \times 0.1 = 1.0\times10^4$ J;

(d) thermal energy required to raise temperature (same as for constant volume);
and to do work against the atmosphere;
so must be larger;
Award [0] for a "bald" statement of answer or fallacious argument.

A3. (a) increase in the degree of disorder (in the system);

(b) total entropy (of the universe);
is increasing;

(c) entropy of surroundings increases by a greater factor;
because process gives off thermal energy / other appropriate statement;

(d) (i) a process in which there is no energy (heat) exchange;
between system and surrounding;
or
all the work done;
either increases or decreases the internal energy of the system;

(ii) a process that takes place at constant volume;

(iii) a process that takes place at constant pressure;

(e) (i) adiabatics: $C \rightarrow D$, $A \rightarrow B$;

(ii) isochoric: $D \rightarrow A$;

(iii) isobaric: $B \rightarrow C$;

(f) work done in one cycle;

(g) $\frac{8400}{40} = 210\text{ J}$;

(h) $Eff = \frac{W}{Q_H}$;

therefore, $Q_H = \frac{210}{0.4} = 525\text{ J}$;

(b) (i) $C \rightarrow D$ vaporization / change of phase to gas (vapour);
$A \rightarrow B$ condensation / change of phase to liquid;
Do not accept answers explaining just the isobaric nature of the change. Explaining the isothermal nature of the changes by using $Q = W$ is not sufficient.

(ii) absorbed $C \rightarrow D$ / $C \rightarrow D$ and $B \rightarrow C$;
ejected $A \rightarrow B$ / $A \rightarrow B$ and $A \rightarrow D$;

(iii) the area enclosed by ABCD;

(j) (i) isochoric / isovolumetric;

(ii) $B \rightarrow C$ absorbed;
$D \rightarrow A$ ejected;
Accept parallel arrows.

(iii) $Q_1 - Q_2 = 3.0$;
$1 - \frac{Q_2}{Q_1} = 0.6$;
$Q_1 = 5.0\,\text{J}$ and $Q_2 = 2.0\,\text{J}$;

Topic 3 Thermal Physics and Option B2 Thermodynamics

Assignment 1 3.1 Thermal Concepts

- **SLIDES 8-16**
  - Concepts: Molecular theory of solids, liquids, gases; phases; internal energy; temperature scale; absolute temperature
  - In your notes workout example **slide 16**
- **SLIDES 17-29**
  - Concepts: specific heat capacity; phase change graphs; specific latent heat
  - In your notes workout examples on **slides 23, 23 and 29**
- **SLIDES 30-34 TOPIC 8.2**
  - Concepts: Three methods of heat transfer
  - Optional: slides 35-46: more examples of convection and its affects

Assignment 2 3.2 Modeling a Gas

- **SLIDES 6-20**
  - Concepts: Pressure; Kinetic model of an ideal gas; moles
  - In your notes workout examples on **slides 7, 8, 19, 20, 21**
- **SLIDES 21-35**
  - Concepts: Avogadro's number; ideal gas equations; real gases;
  - In your notes workout examples on **slides 21, 23, 24, 25, 34**
  - In your notes copy the definitions
    - isobaric (slide 29)
    - isolated (slide 31)
    - isovolumetric (slide 32)
    - isothermal (slide 34)

Assignment 3

- **SLIDES 36-49**
  - Concepts: State change graphs; average KE of a gas
  - In your notes copy the graph with each section labeled on **38**
  - In your notes copy the definitions
    - Thermodynamic cycle (slide 40)
  - In your notes workout examples on **slides 41, 42, 43, 44, 48, 49.**

OPTION C — ENERGY EXTENSION

C1. This question is about a heat engine.

(a) Explain the difference between a *heat engine* and a *heat pump*. *[3]*

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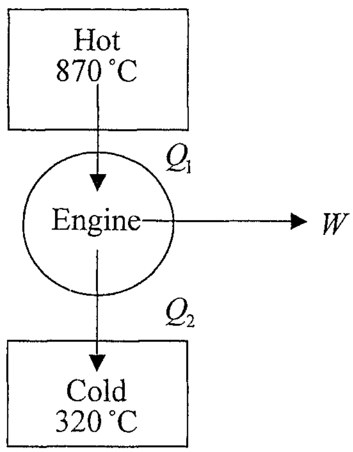
The diagram below represents an idealized heat engine. The engine operates in a Carnot cycle between a hot reservoir at temperature 870 °C and a cold reservoir at temperature 320 °C .



During one cycle, Q_1 is the energy transferred from the hot reservoir, Q_2 is the energy transferred into the cold reservoir and W is the work done by the engine.

(b) Name the law that determines the relationship between Q_1, Q_2 and W. *[1]*

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(This question continues on the following page)

X–38

(Question C1 continued)

(c) The power output for this engine is 100 kW. Determine the rate at which energy is transferred

(i) from the hot reservoir. *[4]*

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(ii) to the cold reservoir. *[2]*

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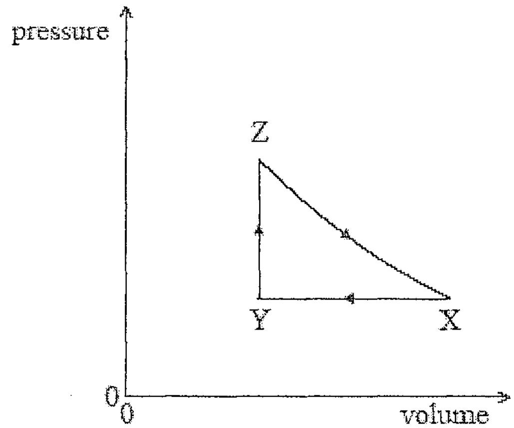
X-39

More Practice Option B2

1. The diagram shows the pressure volume relationship for a fixed mass of an ideal gas that undergoes a cycle XYZ.



In which part(s) of the cycle is external work done **on** the gas?

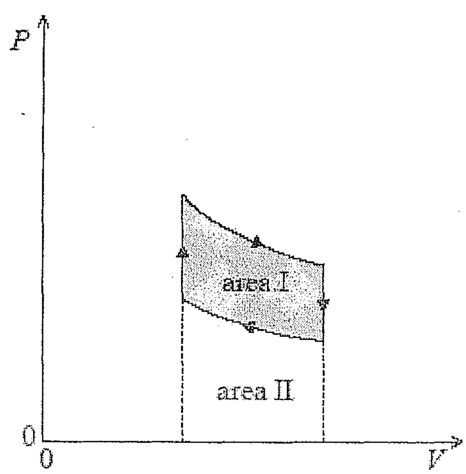
A. Y → Z only

B. Y → Z and Z → X only

C. X → Y and Z → X only

D. X → Y only

2. The diagram shows the pressure–volume (PV) relationship for a gas.



Which of the following area(s) is/are equal to the work done by the gas as it expands?

A. area I

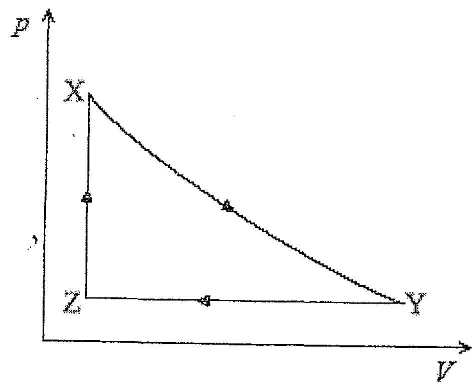
B. area II

C. area I + area II

D. area I – area II

X-40

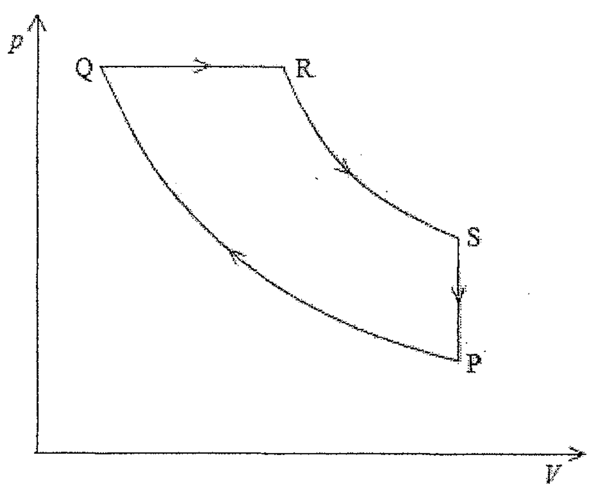
3. The graph below shows the variation of the pressure p with volume V of an ideal gas during one cycle of an engine.



Which of the following correctly names the thermodynamic process associated with the parts Y→Z and Z→X of the cycle?

	Y→Z	Z→X
A.	isobaric	isochoric
B.	isobaric	isothermal
C.	isochoric	isobaric
D.	isochoric	isothermal

4. The diagram shows the pressure/volume (p/V) diagram for one cycle PQRS of an engine.



In which sections of the cycle is work done **on** the engine?

A. SP only

B. PQ only

C. SP and PQ only

D. RS and SP only