Thermodynamics

FIZIKA SJPO Training

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1 Notes

1.1 Temperature and Heat

Thermodynamics is a field of Physics dedicated to the study of how heat, work and temperature interact with one another. It is an extremely broad subject that includes familiar examples such as ice melting, car engines and the Sun. In this handout, we will begin by learning the basics of Thermodynamics . Then, we will explore the mathematical theory behind one of the most famous applications of Thermodynamics: the ideal gas (which air can be approximated as at room temperature). Lastly, we will see some real world application of Thermodynamics in engines and refrigerators.

1.1.1 Temperature

Most of us have a qualitative idea of what temperature is; some things feel "hot" (like a bowl of soup) while some things feel "cold" (like ice). However, scientists need to be able to define temperature properly. A simple way to think of temperature is that it is a measure of the average kinetic energy (due to vibration and motion) of particles in an object. We describe two objects in contact with each other with the same temperature as **thermal equilibrium**. On a side note, you may want to read up on Statistical Mechanics to gain a deeper understanding of what "temperature" really is. Nevertheless, for the scope of Physics Olympiads, it is sufficient to understand temperature with the concepts introduced in this handout.

In our daily lives, we will use the Celsius, °C, to measure the temperature of common objects. However, in Physics, we use another unit more frequently. This unit is called the Kelvin, K, and the conversion between the units are as follows:

$$T \text{ (in Kelvin)} = T \text{ (in Celsius)} + 273.15\text{K}$$

This is called the absolute temperature scale. The number 273.15 arises because this is the lowest temperature that can be attained (0K/-273.15°C). As such, the melting and boiling point of water will be 273.15K and 373.15K respectively.

1.1.2 Thermal Expansion

We may have heard that when objects are heated up, they will expand; when they are cooled, they will contract. This is because atoms in these objects will vibrate more vigorously when they are heated up, and so they are more able to overcome attractive forces between them and thus spread out.

Let us understand a simple case of linear expansion first. Consider a rod with initial length L_0 and temperature T_0. Experiments show that when we heat up the rod by ΔT , the increase in length ΔL is directly proportional to the extent of heating. In other words, we obtain this equation:

$$\Delta L = \alpha L_0 \Delta T$$

α is the coefficient of linear expansion, which is dependent on the material of the rod.

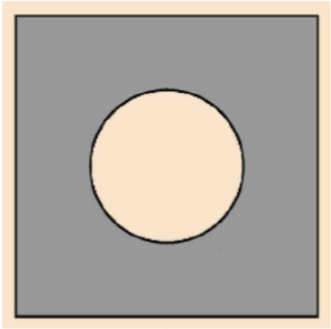
Furthermore, it is also observed that the change in volume ΔV is also proportional to ΔT. So, we obtain a similar equation:

$$\Delta V = \beta V_0 \Delta T$$

β is the coefficient of volume expansion. For most solids, $\beta = 3\alpha$ because changes in each of the three directions contributes to changes in volume. Questions will usually inform you if this assumption can be held.

Note: $\Delta T = T_f - T_i$, so it can be negative when $T_f \leq T_i$ (the object is cooled down). This means ΔL and ΔV are negative as well, indicating that the object has contracted. Additionally, the units used can either be in °C or K, since we are taking the differences of two temperatures.

Example 1.1. A metal sheet with a hole inside is heated up. Does the size of the hole increase or decrease?



Solution. The size of the hole will increase. This is because all length scales of the the object will expand linearly as per the thermal expansion equation, including the cavities and boundaries. One may think that the hole shrinks because the metal expands and pushes the boundaries of the hole inward, but this is not true as this implicitly assumes the edges of the metal are fixed while the rest of the metal expands, while in reality the sheet expands including the inner and outer edges, and necessarily follows the linear expansion equation.

Example 1.2. A glass flask with a volume of $200cm^3$ is filled to the brim with mercury at 20°C. When the temperature of the system is raised to 100°C, does the mercury overflow the flask? By how much will it overflow? The coefficients of volume expansion of the mercury and glass are $1.8 \times 10^{-4}K^{-1}$ and $1.2 \times 10^{-5}K^{-1}$.

Solution. This is a simple application of the formulas we introduced earlier.

$$\Delta V_{mercury} = (1.8{\times}10^{-4})(200)(100\text{-}20){=}2.9\text{cm}^3$$

$$\Delta V_{flask} = (1.2{\times}10^{-5})(200)(100\text{-}20){=}0.19\text{cm}^3$$

To calculate the volume that overflowed, we simply take the difference of these two values.

$$\Delta V_{mercury} - \Delta V_{flask} = 2.9 - 0.19 = 2.7cm^3$$

This example shows how liquid-in-glass thermometers (like the ones used in school laboratories) function: the mercury or alcohol will be heated up and expand in volume, which is then read off the markings printed on the thermometer.

1.1.3 Heat

When objects of two different temperatures are placed together, they will soon reach the same temperature. The substance that is transferred between these objects is known as **heat**. Just as an object can gain or lose energy by receiving and doing work, an object can gain and lose energy through heat. It is important to note that heat refers to the **energy in transit** between two objects.

There are two primary effects of heat. Firstly, heat causes a change in an object's temperature. We call the quantity of heat transferred from one object to another Q (units of J), and the following relationship holds:

$$Q = mc\Delta T$$

c is a material property called **specific heat capacity** and its value will usually be provided if calculations are necessary. When Q is positive, it means an object of mass m has gained heat and its temperature will rise (vice versa).

The next effect of heat is phase changes. This refers to changes in state of an object (melting, freezing, boiling, evaporation and condensation). The relationship used to describe these processes for an object with mass m is:

$$Q = \pm mL$$

L can either be the latent heat of fusion L_f (freezing and melting) or the latent heat of vaporisation L_v (evaporation, boiling and condensation). The positive sign is used when heat is added to the system (solid to liquid to gas) and vice versa. Once again, values of L will be provided.

Example 1.3. 1.2 kg of steam at 100 °C is cooled to ice at 0 °C. What is the total thermal energy lost? (Note: energy lost must be a positive number)

Solution. There are three processes taking place, of which thermal energy is lost for all. Firstly, the steam will condense into water. Secondly, water will be cooled down from 100°C to 0°C. Lastly, water will freeze into ice. The total thermal energy lost is thus:

$$Q_{loss} = |-mL_v| + |mc\Delta T| + |-mL_f|$$

$$\text{|-1.2*2.256 } \times 10^6| + |1.2 * 4.19 \times 10^3 * (0 - 100)| + |-1.2 * 3.34 \times 10^5| = 3.61 \times 10^6 \text{J}$$

1.1.4 Heat Transfer

We have studied how heat affects temperature and phase changes. It is now time to explore the three main modes of heat transfer: conduction, convection and radiation.

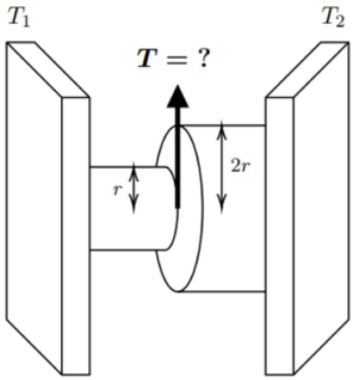
Conduction refers to heat transfer through direct contact with a body. Particles in an object will vibrate vigorously and knock into one another, allowing energy to be transferred across space. The rate at which heat (power with units of W) is transferred, $\Delta Q/\Delta T$ is determined experimentally to be:

$$\frac{\Delta Q}{\Delta t} = kA\frac{T_H - T_C}{L}$$

k is the thermal conductivity of the material, which depends on the material itself. A is the cross sectional area of the object through which heat is flowing, L is the length of the object along which heat is flowing and T_H and T_C are the temperatures of both sides of the object (in either Celsius or Kelvin).

For Olympiad questions, we are often tasked to analyse more complex scenarios. Heat may flow through two successive materials, and we are tasked to find the temperature at the interface of the objects. The key idea to recognise is that at **steady state**, the rate at which heat enters and exits the interface must be the same.

Example 1.4 (SJPO 2025)**.** Two cylinders of radii r and $2r$ are joined along a common axis. They connect two reservoirs which are maintained at temperatures T_1 and T_2 . What is the steady state temperature T of the point at which they are joined? The cylinders have the same length and are made of the same material.



Solution. As mentioned previously, we need to balance the rate at which heat enters with the rate at which heat exits. k and L are stated to be the same, so we analyse the differences due to T_1, T_2 and A. Without loss of generality, let us assume that $T_2 > T > T_1$. The rate at which heat enters the interface from T_2 to T is

$$\frac{\Delta Q_1}{\Delta t} = 4\pi r^2 k \frac{T_2 - T}{L}$$

The rate at which heat exits the interface from T to T_1 is

$$\frac{\Delta Q_2}{\Delta t} = \pi r^2 k \frac{T - T_1}{L}$$

Equating both of these expressions, we obtain

$$T = \frac{T_1 + 4T_2}{5}$$

Convection is the next form of heat transfer. This refers to the transfer of heat by the motion of fluid (air, water) from one place to another. It is generally a complex process, however, Newton's Law of Cooling can be applied in Olympiad problems. It states that

$$\frac{\Delta Q}{\Delta t} = hA(T - T_{env})$$

h is the heat transfer coefficient, a material property while A is the exposed surface area the object has with surrounding air. T_{env} is the temperature of the surrounding air. This equation can be solved using calculus to find the temperature-time graph of the object, but is outside the scope of SJPO.

Radiation is the final form of heat transfer we will discuss. All objects will emit electromagnetic waves and these waves carry energy. As such, objects lose heat through radiation. This relationship is called the Stefan-Boltzmann law:

$$\frac{\Delta Q}{\Delta t} = A\epsilon\sigma T^4$$

A is the surface area of the object, ϵ is emissivity (a dimensionless number that ranges from 0 to 1), σ is the Stefan-Boltzmann constant ($5.6705 \times 10^-8 W m^{-2} K^{-4}$) and T is the temperature of the object in Kelvin. ϵ depends on the material of an object; a shiny metallic surface has a lower ϵ while a black matte surface will have ϵ very near 1.

Consider an object in thermal equilibrium with its surroundings. As mentioned previously, the rate of heat gained is equal to the rate of heat lost to keep temperature T_s constant. As such, an object will gain heat through radiation as well, as shown with this formula:

$$\frac{\Delta Q}{\Delta t} = A\epsilon\sigma T_s^4$$

Example 1.5. The total surface area of a person's body is $1.2m^2$ and his skin's temperature is 30°C. The surrounding air is 20°C. Find the net rate of heat loss by radiation. The emissivity of the body can be approximated as 1.

Solution. This is a straightforward application of the previous formulae. The net rate of heat loss accounts for the heat absorbed from the surroundings

$$\text{Net Rate of Heat Loss} = Ae\sigma(T^4 - T_s^4) = (1.2)(1)(5.67 \times 10^{-8})(303^4 - 293^4) = 72W$$

1.2 Ideal Gases

It is now time for us to study Thermodynamics using the fairly simple and famous model of the ideal gas. The ideal gas model is based on these assumptions: gas particles only interact with each other through **elastic collisions**, there are no intermolecular **attractive forces** and the motion of individual particles are **independent** of each other.

1.2.1 State Equation

Scientists in the past have conducted various experiments to study the properties of gases. Their conclusions can be compressed into a single equation, called the ideal gas equation:

$$PV = nRT$$

It is known as a state equation because it relates various properties of a gas to each other. P is pressure (in Pa), V is volume (in m^3), n is number of moles of gas (in mol), T is temperature (in K; must be **absolute temperature**). R is the ideal gas constant, whose numerical value is $8.3145 Jmol^{-1}K^{-1}$. n is measured using the units mol. One mole (1 mol) of a substance refers to the amount of substance that contains as many elementary particles as there are atoms in 12g of carbon-12. This number is called **Avogadro's number**, $N_A = 6.022 \times 10^{23}$ molecules/mol. This may be confusing, so this analogy may help: A dozen of "something" refers to having 12 of "something", just like how a mole of "something" refers to having 6.022×10^{23} of "something".

Sometimes, we use another form of the ideal gas equation:

$$PV = NkT$$

N is the number of particles and $k = \frac{R}{N_A}$ is the Boltzmann constant, with numerical value of $1.38 \times 10^{-23} JK^{-1}$.

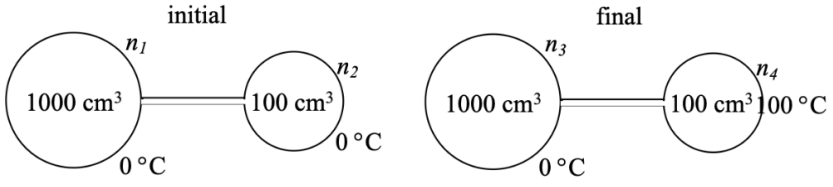
We will now go through a few examples.

Example 1.6. Find the density of air at 20°C and normal atmospheric pressure.

Solution. We must rearrange the ideal gas equation by noting that $n = \frac{m}{M}$ where m is the total mass and M is the molar mass of the gas. Remembering the definition of density: $\rho = \frac{m}{V}$, we obtain this equation

$$\rho = \frac{pM}{RT} = \frac{(1.013 \times 10^5)(28.8 \times 10^{-3})}{(8.314)(20+273.15)} = 1.20 kgm^{-3}$$

Example 1.7. Two gas containers with volumes of 100 cm3 and 1000 cm3 respectively are connected by a tube of negligible volume, and contain air at a pressure of 1000 mmHg. If the temperature of both vessels is originally 0°C, what is the new pressure when the temperature of the smaller containers is raised to 100°C?



Solution. To solve these types of questions, we must always identify which variable (P, V, n, T) **remains constant**. In this case, because the containers are not connected to the surroundings, the total n remains constant. Furthermore, both containers will have the same pressure as they are connected to each other. Using $n = \frac{PV}{RT}$, we write this equality to conserve the total amount of gas:

$$n_1 + n_2 = n_3 + n_4$$
$$\frac{P_1V_1}{RT_1} + \frac{P_1V_2}{RT_1} = \frac{P_2V_1}{RT_1} + \frac{P_2V_2}{RT_2}$$

Substituting in our values, we obtain $P_2 = 1024mmHg$.

1.2.2 Kinetic Theory

Kinetic theory aims to explain the macroscopic properties of gases by modelling them as microscopically tiny particles. The formal mathematics needed to study kinetic theory is outside the SJPO syllabus.

The most important thing to remember from kinetic theory is that

$$KE = \frac{3}{2}nRT = \frac{3}{2}NkT$$

KE is the total translational kinetic energy of a sample of ideal gas, where T is in Kelvin. Because an ideal gas does not have any potential energy, we can conclude that this is also the total energy of an ideal gas.

We can obtain the translational kinetic energy of one particle and relate it to its speed:

$$\frac{3}{2}kT = \frac{1}{2}mv^2$$
$$v = \sqrt{\frac{3kT}{m}}$$

Example 1.8. (a) A tyre has a fixed internal volume of 0.0120 m^3. On a day when the temperature is 25 C the pressure in the tyre has to be increased from 2.62×10^5 Pa to 3.23×10^5 Pa. Assuming the air is an ideal gas, calculate the additional amount of air which has to be supplied.

(b) Show that the kinetic energy of a molecule of air at a temperature of 25 C is 6.17×10^{-21} J. Assume the air behaves as an ideal gas.

(c) Hence, calculate the internal energy of one mole of the air at a temperature of 25 C.

(d) Calculate the increase in the internal energy of the air in the tyre in (a) as a result of increasing its pressure.

Solution. (a) $P_1V = n_1RT$; $P_2V = n_2RT$; $(P_2 - P_1)\ V = (n_2 - n_1)\ RT$

$(3.23 - 2.62) \times 10^5 \times 0.0120 = (n_2 - n_1) \times 8.31 \times (25 + 273.15)$

$(n_2 - n_1) = 0.2954$ mol

Amount of air to be supplied = 0.295 mol

(b) KE per particle $= \frac{3}{2}kT = 1.5 \times 1.38 \times 10^{-23} \times (25 + 273.15) = 6.17 \times 10^{-21}$ J (shown)

(c) KE per mole $= 6.172 \times 10^{-21} \times 6.02 \times 10^{23} = 3.72 \times 10^3$ J

(d) Increase in KE $= 3.716 \times 10^3 \times 0.2954 = 1.10 \times 10^3$ J

1.2.3 Heat Capacities

Remember the equation introduced in Section 1.1.3. We can apply it to gases, but instead of using mass m, we will consider the amount of molecules n. These are called **molar heat capacities**.

There are two ways we can heat up a sample of gas. Firstly, we can heat it up while it is stored in a rigid jar such that its volume doesn't change. This is called C_v, molar heat capacity at **constant volume**. Secondly, we can heat it up while it is kept at the same pressure. This is called C_p, molar heat capacity at **constant pressure**. For a **monotatomic** ideal gas, remember this:

$$C_p = \frac{5}{2}R;\ C_v = \frac{3}{2}R;\ C_p = C_v + R$$

Using this concept, we can easily relate the heat added/removed to the gas to its temperature change:

$$Q = nC_{p/v}\Delta T$$

Another quantity we will use later is called the adiabatic index $\gamma = \frac{C_p}{C_v}$. Its value for a monoatomic gas is $\frac{5}{3}$.

1.2.4 First Law of Thermodynamics

Now that we have studied the ideal gas, let us introduce the **First Law of Thermodynamics**: The internal energy of a system depends only on its state; the increase in the internal energy of a system is the sum of the work done on the system and the heat supplied to the system.

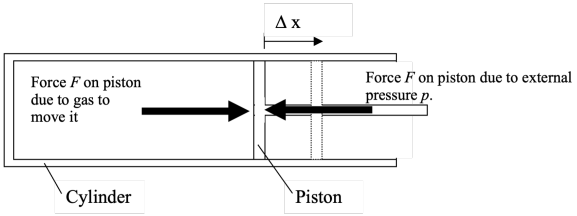
$$\Delta U = Q_{to} + W_{on}$$

This is basically a restatement of the conservation of energy, and will be extremely useful in the following sections. It is also important that we are clear of the signs of each term. The table below summarises key information needed.

	Positive (+)	Negative (–)
ΔU	**Increase** in internal energy	**Decrease** in internal energy
Q	Heat **transferred** to system	Heat **lost** by the system
W	Work done **on** system (compression)	Work done **by** system (expansion)

1.2.5 Thermodynamic Processes

Armed with the First Law of Thermodynamics, we can now analyse various thermodynamic processes. To start off generally, we consider the cylinder of gas below.



When the gas expands, the gas exerts force F on the piston to overcome external pressure. The work done by the force in moving the piston Δx against an external pressure is the work done by the gas. Subsequently,

$$\Delta W_{by} = F\Delta x = PA\Delta x = P\Delta V$$

This can be expressed as an integral:

$$W = \int_{V_1}^{V_2} P\, dV = \text{area under P-V graph}$$

The sign of W is determined using this table

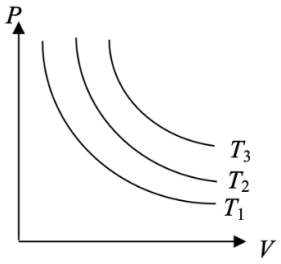
	When gas expands	When gas is compressed
Work done **by** the gas, W_{by}	W_{by} is **Positive**	W_{by} is **Negative**
Work done **on** the gas, W_{on}	W_{on} is **Negative**	W_{on} is **Positive**

Note: $W_{on} = -W_{by}$

Firstly, consider an **isothermal** process. This means that temperature does not change, and thus internal energy of the gas remains constant too ($\Delta U = 0$). If the gas expanded (work done on it is negative), it means that the gas gained heat (and vice versa). The magnitude of work done can be obtained using calculus and is:

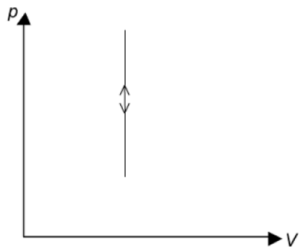
$$W = nRT \ln \frac{V_2}{V_1}$$

Additionally, on the PV graph, $P \propto \frac{1}{V}$ since nRT is a constant.



$T_1 < T_2 < T_3$

Next, consider an **isochoric** process. This means that volume doesn't change, which can be due to the container being rigid. In this case, there is no work done on or by the system because there is no expansion or compression. As such, $\Delta U = Q$.



An **isobaric** process is a process whereby pressure is kept constant. The expression for work is simply:

$$W = P\Delta V$$

ΔV is simply the change in volume of the gas. Once again, it is crucial that you identify the correct sign ($\pm$) to use!

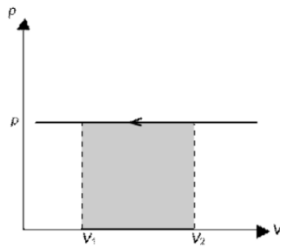


Figure 1: Work done on gas is positive (compression)

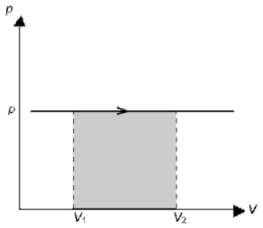


Figure 2: Work done on gas is negative (expansion)

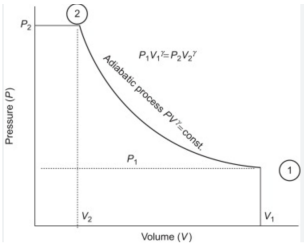
Finally, we have **adiabatic** processes. This occurs when there is no heat exchange with the surroudings, either because the system is insulated or because the process occurs too fast for heat exchange to occur. As such $\Delta U = W$.

It is important that you remember the adiabatic relationship:

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

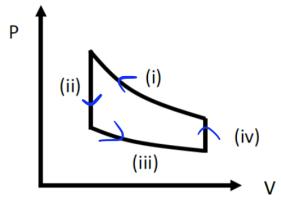
$$TV^{\gamma-1} = \text{constant}$$

Where γ is the adiabatic index introduced earlier.



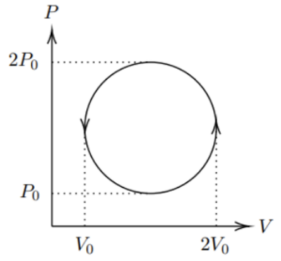
We will see questions involving P-V diagrams a lot. It is crucial that you remember the four special processes as well as the fact that in **cyclical processes** (P-V plot is a closed loop), $\Delta U = 0$**.**

Example 1.9 (SJPO 2018)**.** A refrigerator uses a fixed quantity of an ideal gas and undergoes a cycle, as shown in the diagram below. The parts of the cycle are labelled as: (i) isothermal (same temperature) process (ii) isochoric (same volume) process (iii) isothermal process and (iv) isochoric process. Which part(s) of the cycle has/have heat flowing out of the gas?



Solution. The answer is (i) and (ii). Let us first consider (i) and (iii), the isothermal processes. The gas is compressed in (i), so W_{on} is positive and for $\Delta U = 0$, $Q < 0$ and heat has flowed out of the gas. Next, consider (ii) and (iv), the isochoric processes. No work is done so ΔU is purely due to Q. In (ii), P decreases at constant V, implying that T and thus U has decreased. We can thus conclude that the gas lost heat. Thus, the answer is (i) and (ii).

Example 1.10 (SJPO 2025)**.** A gas undergoes a thermodynamic cycle that is represented by a counter-clockwise circular path on the PV diagram. Throughout the cycle, the gas reaches pressures between P_0 and $2P_0$, and volumes between V_0 and $2V_0$. What is the total heat flow in or out of the gas in one cycle?



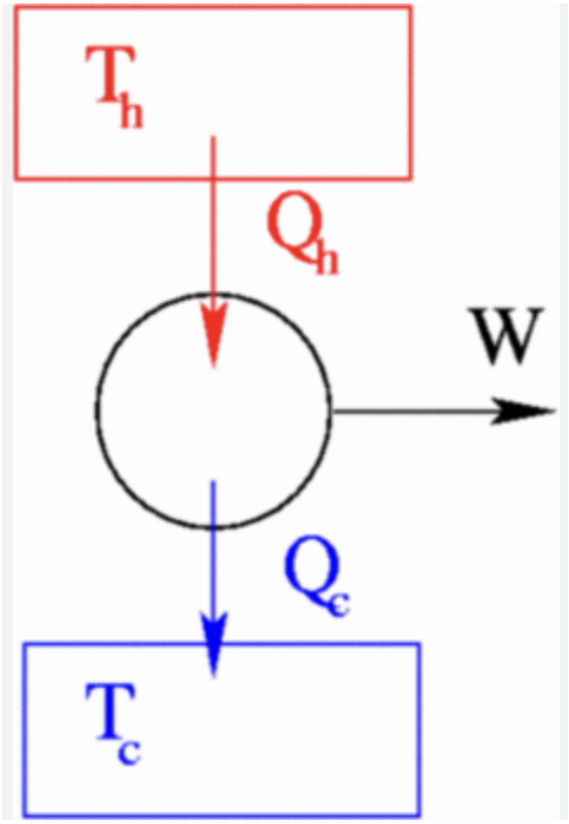
Solution. We must first determine if heat flows in or out of the gas. Since the graph is going counter-clockwise, we conclude that the work done on the gas is positive. For $\Delta U = 0$, heat must flow out of the gas. Next, we know that the magnitude of W and Q are the same. This is basically the area of the enclosed region of the P-V graph: $\frac{1}{4}\pi P_0 V_0$ **out**.

Example 1.11 (SJPO 2013)**.** An ideal gas is heated such that it expands at constant pressure. The gas does work W. What is the amount of heat added to the gas?

Solution. Since $P = \frac{nRT}{V}$ and P is constant, it means that both T and V increased. $\Delta U > 0$ since T rose. Remembering the first law: $\Delta U = Q_{to} + W_{on} = Q + (-W) > 0$. We thus conclude that $Q > W$.

1.3 Engines and Refrigerators

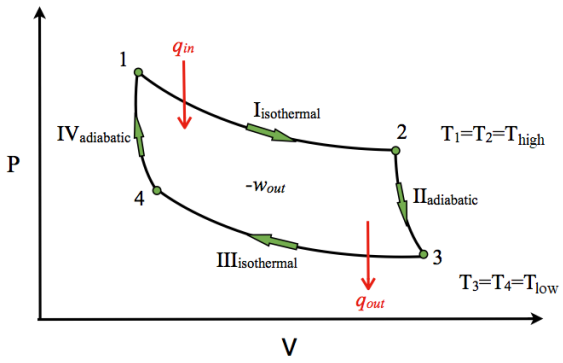
A heat engine is any machine that absorbs heat Q_H from a hot reservoir at T_H and does work W and loses heat Q_C to a cold reservoir at T_C. We are often not interested in how exactly this happens; rather, we use an abstract type of engine as shown in the photo below.



The efficiency of an engine is never greater than 1 and is defined as

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

An important engine you should recognise is called the **Carnot** engine. It operates the Carnot cycle as shown here

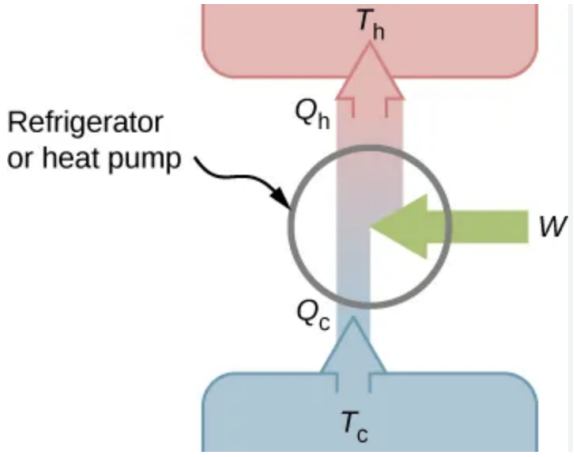


The Carnot engine is most efficient heat engine. This is because it only involves adiabatic and isothermal processes. The efficiency is given by

$$e_{Carnot} = 1 - \frac{T_C}{T_H}$$

The two temperatures are the temperatures of the cold and hot reservoirs respectively.

A refrigerator is any machine that receives work in order to pump heat from a cold reservoir to a hot reservoir.



The coefficient of performance of a refrigerator is a positive number that ranges from 0 to infinity:

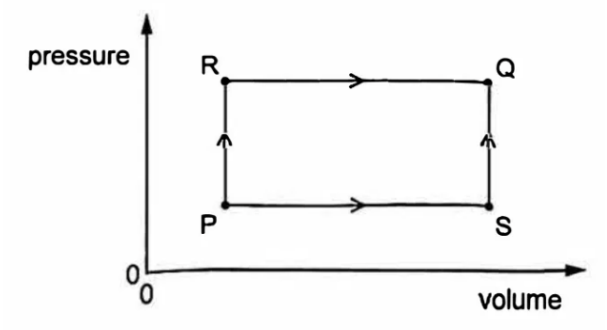
$$COP = \frac{|Q_C|}{|W|} = \frac{|Q_C|}{|Q_H| - |Q_C|}$$

A Carnot engine can be operated in reverse to obtain a Carnot refrigerator:

$$COP = \frac{T_C}{T_H - T_C}$$

2 Problems

Problem 2.1. A fixed mass of gas undergoes changes of pressure and volume as shown.



When the gas is taken from state P to state Q by the stages PR and RQ, 3 J of work is done by it and there is a thermal transfer of 8 J of energy into it.

When the same resultant change is achieved by stages PS and SQ, 1 J of work is done by the gas.

In this case, what is the thermal transfer of energy?

(A) 4 J out of the gas

(B) 6 J into the gas

(C) 8 J into the gas

(D) 10 J into the gas

Problem 2.2. A sample of gas is compressed slowly in a metal cylinder. W is the amount of work done on the gas. During the compression, the internal energy of the gas increases by ΔU.

How much heat is transferred from the gas to the surroundings?

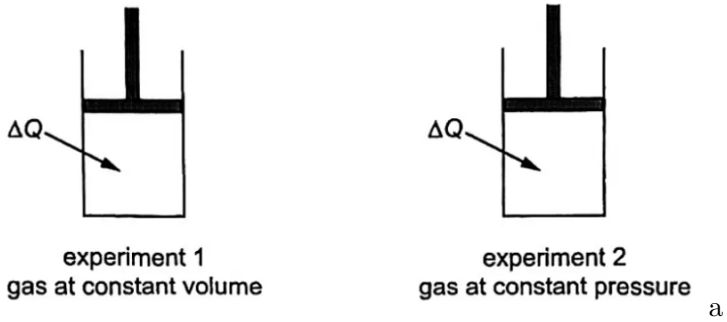
(A) $W + \Delta U$

(B) $W - \Delta U$

(C) $-W + \Delta U$

(D) $-W - \Delta U$

Problem 2.3. Two experiments are carried out using a fixed mass of gas.



a

In experiment 1, an amount of heat energy ΔQ is supplied to a fixed mass of gas at constant volume. In experiment 2, the same amount of heat energy ΔQ is supplied to the same mass of gas at constant pressure.

Which statement about these two experiments is correct?

(A) The work done by the gas in experiment 1 is greater than ΔQ.

(B) The increase in internal energy of the gas in experiment 1 is equal to ΔQ.

(C) The work done by the gas in experiment 2 is greater than ΔQ.

(D) The increase in internal energy of the gas in experiment 2 is equal to ΔQ.

Problem 2.4. An airgun pellet, of mass m and specific heat capacity c, hits a steel plate at speed v. During the impact, 50% of the pellet's kinetic energy is converted to thermal energy in the pellet. What is the rise in temperature of the pellet?

(A) $\dfrac{v^2}{2c}$

(B) $\dfrac{v^2}{4c}$

(C) $\dfrac{mv^2}{2c}$

(D) $\dfrac{mv^2}{4c}$

Problem 2.5. An ideal gas has an internal energy U at 0 °C. The gas is heated to 273 °C. What is the internal energy of the gas at 273 °C?

(A) $\sqrt{2}\,U$

(B) $2U$

(C) $4U$

(D) $273U$

Problem 2.6. Thermal energy is supplied to 5.00 kg of water at 30.0 °C. All of this water becomes steam at 100 °C. There is no heat loss to the surroundings.

Specific heat capacity of water = $4190\,\mathrm{J\,kg^{-1}\,K^{-1}}$.

Specific latent heat of vaporisation of water = $2260\,\mathrm{kJ\,kg^{-1}}$.

How much thermal energy is supplied to the water?

(A) 1.48×10^6 J

(B) 3.73×10^6 J

(C) 1.13×10^7 J

(D) 1.28×10^7 J

Problem 2.7. A beaker containing 180 g of water at 25 °C has a 20 g ice cube at 0 °C added to it. No heat is transferred between the water and the surroundings (including the beaker). What is the final temperature of all the water in the beaker after all the ice has melted?

(Take the specific heat capacity of water to be $4\,\mathrm{J\,g^{-1}\,°C^{-1}}$ and the specific latent heat of fusion of water to be $300\,\mathrm{J\,g^{-1}}$.)

(A) 2.5 °C

(B) 8.3 °C

(C) 10.0 °C

(D) 15.0 °C

(E) 16.7 °C

(F) 22.5 °C

Problem 2.8 (SJPO 2022)**.** It is recommended to use water of approximately 80 °C to make green tea. This can be prepared by mixing x litres of water at room temperature ($28\check{r}C$) with every litre of water at 100 °C. Neglecting the small changes in the density of water as its temperature changes, the value of x is__.

(A) 0.5

(B) 0.4

(C) 0.2

(D) 2.6

(E) unable to be obtained

Problem 2.9 (SJPO 2022)**.** An iron ring is to fit tightly on a cylindrical iron rod. At 25 °C, the diameter of the rod is 6.492 cm and the inside diameter of the ring is 6.480 cm. To slip over the rod, the ring must be larger than the rod diameter by about 0.008 cm. To what temperature must the ring be heated? Take the coefficient of linear expansion of iron $= 12 \times 10^6/K$

(A) 230 °C

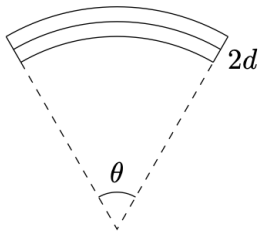
(B) 257 °C

(C) 282 °C

(D) 303 °C

(E) 448 °C

Problem 2.10 (SJPO 2024)**.** A bimetallic strip is made up of two metals with linear expansion coefficients α_1 and α_2, with $\alpha_1 > \alpha_2$. Each metal strip is initially straight with length L_0 and thickness d, where $d << L_0$. The bimetallic strip is heated uniformly such that its temperature rises by ΔT, causing it to bend with an angle of curvature θ as shown below. Find θ.



(A) $\frac{L_0}{d}(\alpha_1 - \alpha_2)\Delta T$

(B) $\frac{d}{L_0}(\alpha_1 - \alpha_2)\Delta T$

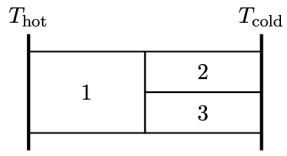
(C) $\frac{d}{L_0}(\alpha_1 + \alpha_2)\Delta T$

(D) $d(1 + \alpha_1 + \alpha_2)\Delta T$

(E) $L_0(1 + \alpha_1 + \alpha_2)\Delta T$

Problem 2.11 (SJPO 2024)**.** Three metal slabs are placed in thermal contact between a hot reservoir of temperature $T_{hot} = 100°C$ and a cold reservoir of temperature $T_{cold} = 20°C$. The slabs have thermal conductivity $k_1 = 200Wm^1K^1$, $k_2 = 400Wm^1K^1$ and $k_3 = 600Wm^1K^1$

respectively. The slabs have the same horizontal length and thickness, but slabs 2 and 3 each have half the vertical length of sheet 1. Neglecting any temperature variation in the vertical direction, find the equilibrium temperature at the centre where all three slabs meet.



(A) 40°C

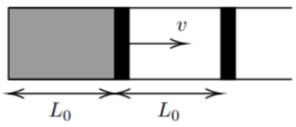
(B) 50°C

(C) 60°C

(D) 70°C

(E) 80°C

Problem 2.12 (SJPO 2025)**.** A monatomic ideal gas is placed in the chamber of a piston with length L_0. The piston is not insulated, so the gas is free to exchange heat with its surroundings. Initially the gas is at equilibrium with pressure P_0. The piston is now moved outwards with speed v, causing the gas to expand, until a length $2L_0$ is reached.



In the limit $v \to 0$, what is the pressure of the gas at the moment the piston reaches length $2L_0$?

In the limit $v \to \infty$, what is the pressure of the gas at the moment the piston reaches length $2L_0$? (Different answers for each)

(A) $0.25P_0$

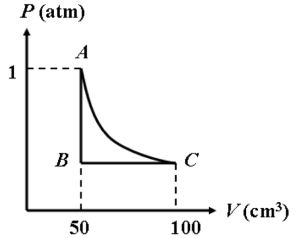
(B) $0.31P_0$

(C) $0.50P_0$

(D) $2.0P_0$

(E) $3.2P_0$

Problem 2.13 (SJPO 2009)**.** 0.02 moles of an ideal gas undergo a cycle consisting of an isochoric process, an isobaric process, and an isothermal process as shown below. Volumes and pressures at specific points are indicated on the axes. The pressure at point B is closest to:



(A) 1.0 atm

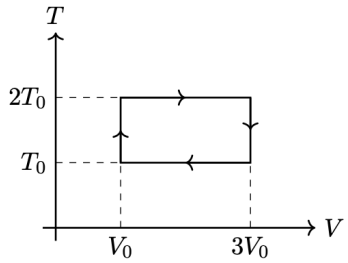
(B) 1.5 atm

(C) 0.2 atm

(D) 0.1 atm

(E) 0.5 atm

Problem 2.14 (SJPO 2024)**.** An ideal gas undergoes a heat cycle that is represented by the following TV diagram.



In one cycle, (?) of work is done (?).

(A) $2nRT_0$, by the gas

(B) $2nRT_0$, on the gas

(C) $3nRT_0$, by the gas

(D) $3nRT_0$, on the gas

(E) $1.5nRT_0$, on the gas

Problem 2.15 (SJPO 2024)**.** A planet of radius r and surface temperature T_P orbits a sun of radius R and surface temperature T_s. The distance between the planet and the sun is d, where $d >> r, R$. Assuming that the planet and the sun are both ideal blackbodies, find the ratio $T_P : T_S$ at equilibrium.

(A) $\sqrt{\dfrac{R}{r}}$

(B) $\sqrt{\dfrac{R}{d}}$

(C) $\sqrt{\dfrac{R}{2d}}$

(D) $\sqrt[4]{\dfrac{R^2}{2d^2}}$

(E) $\sqrt[4]{\dfrac{R^2}{2r^2}}$

Problem 2.16 (SJPO 2024)**.** Zeyuan has a balloon with perfectly elastic and insulating walls. He first fills the balloon at sea level with air at temperature $T_0 = 300K$ and seals it airtight. He then immerses the balloon underwater to a depth of h = 10 m. Find the final temperature of the air in the balloon. Assume that air is diatomic.

(A) 247 K

(B) 256 K

(C) 300 K

(D) 349 K

(E) 364 K

Problem 2.17 (SJPO 2024)**.** Two vessels of equal volumes are connected together by a tube and contain a total of N ideal gas molecules. Initially, both vessels have equal temperatures. The temperatures of the vessels are then changed and maintained at $T_1 = 250$ K and $T_2 = 350$ K respectively. As a result, the molecules redistribute themselves across the two vessels. What is the net number of molecules that are eventually transferred between the vessels?

1. $\frac{1}{12}N$
2. $\frac{2}{7}N$
3. $\frac{2}{5}N$
4. $\frac{5}{12}N$
5. $\frac{5}{7}N$

Problem 2.18 (SJPO 2009)**.** The total energy of a blackbody radiation source is collected for one minute and use to heat water. The temperature of the water increases from 20.0°C to 20.5°C. If the absolute temperature of the blackbody have doubled and the experiment is repeated, which of the following statements would be most nearly correct?

(A) The water would boil within the one-minute time period.

(B) The temperature of the water would increase from 20°C to a final temperature of 21°C.

(C) The temperature of the water would increase from 20°C to a final temperature of 24°C.

(D) The temperature of the water would increase from 20°C to a final temperature of 28°C.

(E) The temperature of the water would increase from 20°C to a final temperature of 36°C.

Problem 2.19 (SPhO 2024)**.** One mole of helium gas, initially at state A where pressure is 101.3 kPa and temperature is 5.0 °C, undergoes a process in which pressure falls to half its initial value at constant volume to state B. It then expands at the same pressure, doubling its volume, to state C.

(a) Calculate the total work done by the gas. (b) Suppose the gas undergoes a process from state A to state C at constant temperature, determine the work done by the gas.

(Hint: draw out the process on a P-V graph)