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Teacher view

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 Notebook

B. The particulate nature of matter / B.4 Thermodynamics (HL)

 Glossary

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Reading
assistance

   (<https://intercom.help/kognity>)  

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- The big picture (HL)
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The big picture (HL)

Higher level (HL)

? Guiding question(s)

- How can energy transfers and energy storage within a system be analysed?
- How can the future evolution of a system be determined?
- In what way is entropy fundamental to the evolution of the universe?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

What do you think the ultimate fate of the universe will be? Watch **Video 1** to see what scientists think may happen.

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Video 1. The possible fates of the universe.

Imagine you are observing the temperatures of objects and their interactions as a result of heat transfers. If you were to construct a law describing the general rule, what would the law be?

Figure 1 and **Interactive 1** show two scenarios for you to think about. Spend a couple of minutes thinking about the following questions, then discuss them with your classmates.

- In **Figure 1**, where is heat being transferred from and to? How will the temperature change?
- In **Interactive 1**, why is work being done on the gas during compression? What difference would it make if the compression was done very quickly rather than very slowly?

Click on 'Show or hide solution' to see the answers.



Figure 1. An ice cold glass (0°C) with hot water (90°C) in a room at 20°C .

Credit: Sergii Tverdokhlibov, Getty Images



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Interactive 1. The Gas Inside a Sealed Syringe Is Being Compressed and Expanded.

More information for interactive 1

The animation video shows a sealed syringe containing gas with a movable piston. The piston moves back and forth, demonstrating the compression and expansion of the gas inside. As the piston is pushed inward, the gas particles are forced into a smaller volume, causing them to move closer together. This represents an increase in pressure and temperature due to the work done on the system. When the piston is pulled outward, the gas expands, and the particles spread out, reducing the pressure and temperature. The animation visually represents the relationship between volume, pressure, and temperature in a closed system and highlights how mechanical work can be converted into thermal energy.

- In **Figure 1**, thermal energy is transferred from the hot water to the cold glass and the cool room. Objects at different temperatures in contact with one another will eventually reach an equilibrium, i.e. the same temperature.
- In **Interactive 1**, work is done to compress the gas to reduce its volume and move the particles closer together (increasing potential energy). The energy transfer results in an increase in temperature during the compression (increasing kinetic energy). When there is work done on a system, mechanical energy can be transferred to thermal energy. When the piston compresses the gas rapidly, the amount of work done is the same but the rate of energy transfer is greater so the temperature will rise more rapidly than if the compression is done slowly.

Prior learning

Before you study this subtopic, make sure that you understand the following:

- Principle of conservation of energy (see [subtopic A.3](#) (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43083/)).
- Average kinetic energy of particles (see [subtopic B.1](#) (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43777/)).
- Ideal gas law involving pressure, volume, number of moles, temperature and internal energy (see [subtopic B.3](#) (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43778/)).



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B. The particulate nature of matter / B.4 Thermodynamics (HL)

Internal energy and work done (HL)

B.4.2: Work done by or on a closed system (HL) B.4.3: Change in internal energy of a system (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Understand that the change in internal energy of a system is related to a change in temperature, and calculate change in internal energy.
- Understand that the work done by or on a closed system can be described in terms of pressure and change of volume.

Video 1 shows the explosion of balloons filled with a mixture of hydrogen and oxygen.

Three Hydrogen and Oxygen balloon explosions



Video 1. Hydrogen and oxygen balloon explosions.

More information for video 1

The video demonstrates how balloons filled with hydrogen and oxygen explode. Set in a gymnasium, three evenly spaced stanchions each support a red, green, and blue balloon filled with the gases.

A person wearing a white lab coat steps into view, equipped with safety goggles and ear protection. In their hands is a wooden dowel with a lighter attached to the end, highlighting the importance of caution and controlled handling when working with reactive materials. The demonstration begins as they ignite the lighter and carefully bring the flame beneath the blue balloon. As soon as the flame makes contact, the balloon bursts with a loud bang, its remnants falling to the ground. The process is then repeated with the green balloon, followed by the red one. Each balloon explodes on contact with the same sharp sound, scattering its remnants.



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What are the energy transfers in the explosion? Click on 'Show or hide solution' to see the answer.

The chemical potential energy stored in the hydrogen molecule bonds and the oxygen molecule bonds is released as thermal energy, light energy and sound energy (which is the kinetic energy of the air particles).

A rocket scientist would design a propulsion system based on the same combustion of hydrogen and oxygen, but in a more controlled way. Watch **Video 2** to see the hydrogen and oxygen mixture used in a rocket.

NASA's Artemis I Mission, powered by Boeing-built Space Launch Sy...



Video 2. Hydrogen and oxygen used in a rocket.

Section

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Feedback

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More information for video 2

Assign

1

00:00:00,434 --> 00:00:02,102

[soft music plays]

2

00:00:02,369 --> 00:00:04,705

John F. Kennedy: We set sail on this new sea

3

00:00:06,340 --> 00:00:09,276

because there is new knowledge

to be gained

4

00:00:10,410 --> 00:00:11,979

and new rights to be won,

5

00:00:14,515 --> 00:00:18,819

and they must be won and used

for the progress of all people.

6

00:00:21,755 --> 00:00:24,391

The exploration of space



Student view

will go ahead for the eyes
7
00:00:24,925 --> 00:00:26,493
of the world
8
00:00:27,327 --> 00:00:30,464
now look into space to the moon
9
00:00:30,898 --> 00:00:32,399
and to the planets beyond.
10
00:00:34,168 --> 00:00:35,169
[music swells]
11
00:01:14,908 --> 00:01:17,177
[crowd cheers]
12
00:01:33,727 --> 00:01:35,796
[soft music plays]
13
00:02:18,205 --> 00:02:19,806
[music fades out]

This is another big blast. When the rocket is propelled upwards, there is useful work done on the rocket by the fuel.

In the rocket launch, some of the chemical energy is transferred to thermal energy and sound energy. Is it possible to build a rocket engine that is 100% efficient? See [section A.3.3 \(/study/app/math-aa-hl/sid-423-cid-762593/book/power-and-efficiency-id-43086/\)](#) for how to calculate efficiency. Is there a limit to the efficiency that can be achieved?

In order to know this, we need to understand the type of system that exist in thermodynamics, and to explore the change in internal energy of an ideal gas and the work done during the expansion or compression of a gas.

Work done on or by a gas

There are three types of thermodynamic system:

- Open system: a system that can exchange thermal energy (heat), work and matter (mass) with its surroundings. An example could be a jet engine directing hot gas behind an aeroplane.
- Closed system: a system that can exchange thermal energy or work with its surroundings, but not matter. An example might be a metal container with warm gas inside, cooling down.
- Isolated system: a system that cannot exchange thermal energy, work or matter with its surroundings. An example might be a very effective thermos flask that is well insulated.

Figure 1 shows the three types of system.



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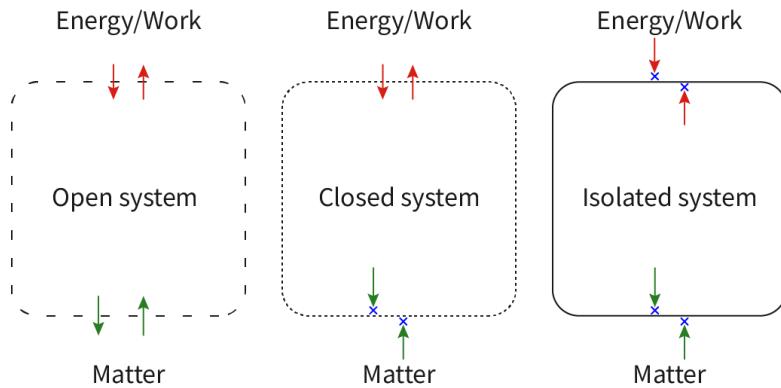


Figure 1. The three types of thermodynamic system.

[More information for figure 1](#)

This diagram illustrates the three types of thermodynamic systems: open, closed, and isolated. There are three boxes side-by-side.

1. Open System:

2. Dotted outline box labeled "Open system."
3. Arrows are shown going in and out of the box for both "Energy/Work" (top) and "Matter" (bottom).
4. This represents that both energy and matter can enter and exit an open system.

5. Closed System:

6. Dashed outline box labeled "Closed system."
7. Arrows are shown going in and out only for "Energy/Work" (top).
8. A single arrow labeled "Matter" points inward, depicting that energy exchange can occur, but matter can only enter and not leave.

9. Isolated System:

10. Solid outline box labeled "Isolated system."
11. Arrows with an "X" on both inward and outward directions for both "Energy/Work" and "Matter."
12. This represents that neither energy nor matter can enter or exit the system.

The arrows in these systems indicate the direction of potential energy and matter exchange, highlighting the unique characteristics of each thermodynamic system type.

[Generated by AI]

How we solve problems related to thermodynamic systems depends upon the type of system we have. Typically we will deal with closed or isolated systems.



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Change in internal energy of an ideal gas

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Making connections

The assumptions used in the ideal gas model are discussed in [subtopic B.3](#) ([/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44289/](#)). One of the most important ideas is that there are no intermolecular forces between the gas particles, so the internal energy of an ideal gas is only due to the kinetic energy of the particles.

The average kinetic energy E_k of particles is given by ([subtopic B.1](#) ([/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43777/](#)):

$$E_k = \frac{3}{2} k_B T$$

where:

k_B = Boltzmann constant, 1.38×10^{-23} J K $^{-1}$

T = absolute temperature, kelvin (K)

For a monatomic ideal gas, the relationship between internal energy, U , and number of molecules, N , is ([subtopic B.3](#) ([/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44289/](#)):

$$U = \frac{3}{2} N k_B T$$

The relationship between internal energy, U , and amount of substance in moles, n , is ([subtopic B.3](#) ([/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44289/](#)):

$$U = \frac{3}{2} n R T$$

The change in internal energy, ΔU , of an ideal gas can be related to its change in temperature, ΔT , with the equations in **Table 1**.

Table 1. Change in internal energy equations.



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Equation	Symbols	Units
$\Delta U = \frac{3}{2} N k_B \Delta T$ $= \frac{3}{2} n R \Delta T$	ΔU = change in internal energy N = number of particles	joules (J) Unitless
k_B = Boltzmann constant, 1.38×10^{-23} J K $^{-1}$		Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet
ΔT = change in temperature		kelvin (K)
n = number of moles		moles (mol)
R = gas constant, 8.31 J K $^{-1}$ mol $^{-1}$		Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet

Study skills

Note that only monatomic ideal gases will be quantitatively analysed in this subtopic.
B.4. Monatomic gases are composed of single atoms only, for example, helium and argon.

Worked example 1

In a closed system, 2.0 moles of helium (He) gas is heated from 27 °C to 41 °C. Calculate the change in internal energy.

Solution steps	Calculations
<p>Step 1: Write out the values given in the question and convert the values to the units required for the equation (Note: When performing a subtraction, it is not necessary to convert temperatures to kelvin. But be careful! In other calculations, ones where multiplication is used, for example, we must convert to kelvin to obtain the correct answer.)</p>	$R = 8.31 \text{ J K}^{-1} \text{ mol}^{-1}$ $n = 2.0$ $T_1 = 27^\circ = 273 + 27 = 300 \text{ K}$ $T_2 = 41^\circ = 273 + 41 = 314 \text{ K}$ $\Delta T = 314 - 300 = 14 \text{ K}$



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Solution steps	Calculations
Step 2: Write out the equation.	$\Delta U = \frac{3}{2}nR\Delta T$
Step 3: Substitute the values given.	$= \frac{3}{2} \times 2.0 \times 8.31 \times 14$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 349.02 \text{ J} = 350 \text{ J}$ (2 s.f.)

💡 Theory of Knowledge

The pie chart shows that air mostly consists of non-monatomic gases, such as nitrogen and oxygen (which are also not ideal gases in practice). Why do you think the ideal gas model is often applied? Can you think of other situations where a simpler model is more helpful than a complex model?

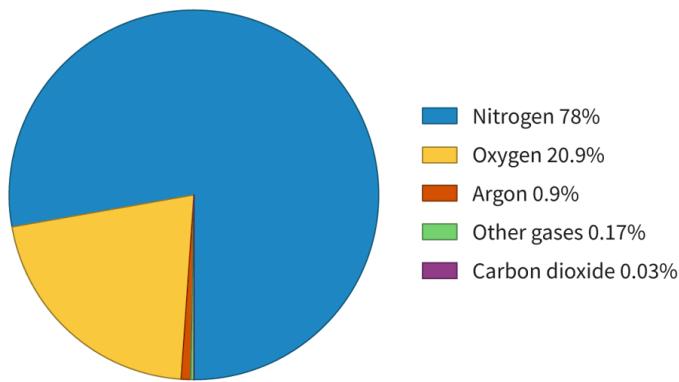


Figure 2. Composition of air.

🔗 More information for figure 2

The image is a pie chart illustrating the composition of air, divided into sections that represent various gases. The largest section, colored blue, represents Nitrogen, which makes up 78% of air. The second largest section, colored yellow, represents Oxygen at 20.9%. A small orange section represents Argon at 0.9%. An even smaller green section stands for Other gases at 0.17%, and the smallest purple section denotes Carbon dioxide, comprising 0.03% of air. The chart provides a visual representation of how these gases contribute to the overall makeup of Earth's atmosphere.

[Generated by AI]

Worked example 2

In a closed system, 2×10^6 molecules of argon are measured to be at a temperature of 30 °C. The internal energy is doubled. What is the new temperature of the argon gas?



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Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$N = 2 \times 10^6$ molecules $T = 30^\circ\text{C}$ $= 303 \text{ K}$
Step 2: Write out the equation.	$\Delta U = \frac{3}{2} N k_B \Delta T$
Step 3: Substitute the values given.	$2 \times U_1 = U_2 = (6/2) N k_B T_1$ $\left(2 \times \frac{3}{2}\right) \times N \times k_B \times 303 = \left(\frac{3}{2}\right) N \times k_B \times T_2$ Cancel by $\left(\frac{3}{2}\right)$, N and k_B : $2 \times 303 = T_2$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$T_2 = 606 \text{ K}$ $= 333^\circ\text{C}$

We are now going to look at the work done on or by a closed system. The surroundings are everything that is not included in the system.

Consider a fixed mass of gas in a container with a frictionless piston (**Figure 3**).

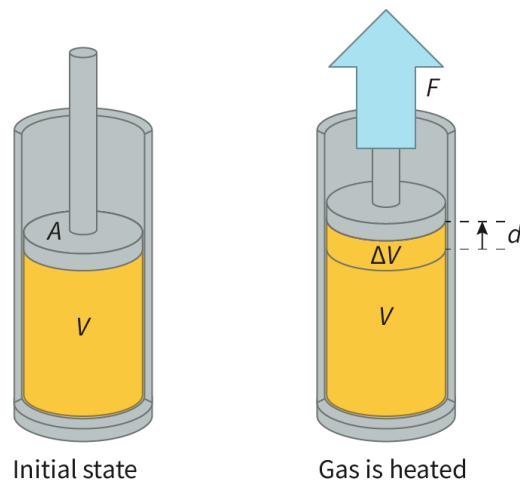


Figure 3. A fixed mass of gas in a container with a frictionless piston.

[More information for figure 3](#)

The diagram shows two vertical cylindrical containers, each with a piston on top. The first container is labeled 'Initial state' and the piston sits at the bottom with volume 'V' and area 'A' marked. The second container is labeled 'Gas is heated', with the piston raised, showing additional volume ' ΔV ' above the original 'V'. An upward arrow labeled 'F' indicates force exerted



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on the piston. An arrow with a distance 'd' denotes the displacement of the piston.

[Generated by AI]

In the 'Initial state' diagram, the gas is at atmospheric pressure so there is no net force on the piston, and it does not move.

In the 'Gas is heated' diagram, when the gas is heated, it expands, and the force exerted on the piston pushes it upwards. Work, W , is done by the gas on the piston.

The equation for work done is ([subtopic A.3 \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43083/\)](#)):

$$W = Fs$$

The equation for pressure is ([subtopic B.3 \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44289/\)](#)):

$$P = \frac{F}{A} \text{ and } F = PA$$

Work done is therefore:

$$\begin{aligned} W &= Fs \\ &= PAs \end{aligned}$$

The change in volume $\Delta V = As$, so we can convert to the equation in **Table 2**.

Table 2. Equation for work done.

Equation	Symbols	Units
$W = P\Delta V$	W = work done	joules (J)
	P = pressure	pascals (Pa)
	ΔV = change in volume	cubic metres (m^3)

If the piston is pushed downwards, the gas is compressed. Work is done on the gas by the piston.

- Positive W means that work is done **by** the gas as it expands.
- Negative W means that work is done **on** the gas by compressing it.

Positive work and negative work are shown in **Figure 4**.



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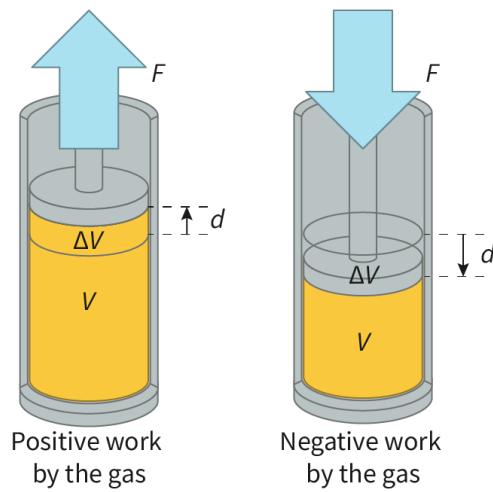


Figure 4. Positive work and negative work.

More information for figure 4

The image shows two cylindrical piston setups demonstrating positive and negative work by gas. On the left, the positive work is represented by an upward piston moved by force (F) and a change in volume (ΔV) with distance (d), with initial volume (V). The color-coded sections indicate ΔV above V . An upward arrow signifies the upward piston movement. On the right, the negative work is depicted with a downward-moving piston under downward force (F) and change in volume (ΔV) with distance (d), again with initial volume (V). A downward arrow symbolizes the piston pushed down. Labels "Positive work by the gas" and "Negative work by the gas" are below each diagram respectively.

[Generated by AI]

Worked example 3

A gas occupying 0.01 m^3 is compressed to half its volume. The gas pressure remains constant at $1 \times 10^5 \text{ Pa}$. What is the work done on the gas?

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$V_1 = 0.01 \text{ m}^3$ $V_2 = \frac{1}{2} \times 0.01 \text{ m}^3$ $= 0.005 \text{ m}^3$ $= 5 \times 10^{-3} \text{ m}^3$ $P = 1 \times 10^5 \text{ Pa}$ $\Delta V = 5 \times 10^{-3} - 0.01$ $= -5 \times 10^{-3} \text{ m}^3$
Step 2: Write out the equation.	$W = P\Delta V$
Step 3: Substitute the values given.	$= 1 \times 10^5 \times (-5 \times 10^{-3})$



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Solution steps	Calculations
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= -500 \text{ J}$ (1 s.f.) The work done is negative as it is being done on the gas.

Work through the activity to check your understanding of change in internal energy.

Activity

- **IB learner profile attribute:**
 - Inquirer
 - Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 15 minutes
- **Activity type:** Pair activity

Instructions:

Two balloons, one filled with air and one filled with helium, are cooled in liquid nitrogen (77 K). Discuss how you think they will behave and try to explain your ideas using particle behaviour. Click the 'Show or hide tip' button for a hint.

Think about which particles will be travelling slowest, and will therefore be most affected by intermolecular forces at the temperature of liquid nitrogen.

Watch the video and see if your prediction is correct. If not, try to offer a new explanation and exchange ideas with another pair.



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Video 3. Cooling balloons in liquid nitrogen..

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5 section questions ^

Question 1

HL Difficulty:

The change in internal energy of an ideal gas is due to the change in the 1 average kinet... ✓ of the particles because there are no 2 intermolecula... ✓ between the particles.

Accepted answers and explanation

#1 average kinetic energy

#2 intermolecular forces

General explanation

In an ideal gas, there are no intermolecular forces between the particles so the change in internal energy is due to the change in the average kinetic energy of the particles only. The change in internal energy of an ideal gas can be related to its change in temperature and the temperature is related to the average kinetic energy

Question 2

HL Difficulty:

2.0 moles of an ideal gas is heated from 56 °C to 110 °C. Determine the change in internal energy. Give your answer to an appropriate number of significant figures.

The change in internal energy is 1 1300 ✓ J.

Accepted answers and explanation

#1 1300

1,300

General explanation

$$\begin{aligned}T_1 &= 56 + 273 \\&= 329 \text{ K}\end{aligned}$$

$$\begin{aligned}T_2 &= 110 + 273 \\&= 383 \text{ K}\end{aligned}$$

$$\begin{aligned}\Delta T &= 383 - 329 \\&= 54 \text{ K}\end{aligned}$$



✖ $\Delta U = \frac{3}{2}nR\Delta T$
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$$= \frac{3}{2} \times 2.0 \times 8.31 \times 54$$

$$= 1346.2 \text{ J}$$

$$= 1300 \text{ J (2 s.f.)}$$

Question 3

HL Difficulty:

300 J of energy is added to 3 moles of an ideal monatomic gas. The original temperature of the gas is 20 °C.
 What is the new temperature of the gas in degrees Celsius?

The new temperature is 1 28 ✓ °C.

Accepted answers and explanation

#1 28

General explanation

$$\Delta U = +300 \text{ J}$$

$$n = 3 \text{ moles}$$

$$T = 20 \text{ }^{\circ}\text{C}$$

$$= 293 \text{ K}$$

Using the equation:

$$\Delta U = \frac{3}{2}nR\Delta T$$

Substitute the values:

$$300 = \left(\frac{3}{2}\right) \times 3 \times 8.31 \times \Delta T$$

$$\Delta T = 8.0 \text{ K}$$

$$T_2 = T_1 + \Delta T$$

$$= 293 + 8$$

$$= 301 \text{ K}$$

$$T = 28 \text{ }^{\circ}\text{C}$$

Question 4

HL Difficulty:

Determine the work done by a gas if it expands from a volume of 0.25 m³ to a volume of 1.0 m³ at a constant pressure of 150 kPa. Give your answer to an appropriate number of significant figures.

The work done is 1 110 ✓ kJ.

Accepted answers and explanation

#1 110

General explanation

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$$\begin{aligned} P &= 150 \text{ kPa} \\ &= 1.5 \times 10^5 \text{ Pa} \\ V_1 &= 0.25 \text{ m}^3 \\ V_2 &= 1.0 \text{ m}^3 \\ \Delta V &= (1.0 - 0.25) \\ &= 0.75 \text{ m}^3 \\ W &= P\Delta V \\ &= 1.5 \times 10^5 \times 0.75 \\ &= 112\,500 \text{ J} \\ &= 110 \text{ kJ (2 s.f.)} \end{aligned}$$

Question 5

HL Difficulty:

A fixed mass of gas at a constant pressure of $1.0 \times 10^5 \text{ Pa}$ is placed in a tube sealed by a frictionless piston, which is free to move. The gas occupies a volume of 0.015 m^3 at a temperature of 20°C . It is heated to 90°C and expands. Determine the work done by the gas on the piston. Give your answer to an appropriate number of significant figures.

The work done by the gas is 1 360 ✓ J

Accepted answers and explanation

#1 360

General explanation

$$\begin{aligned} P &= 1.0 \times 10^5 \text{ Pa} \\ V_1 &= 0.015 \text{ m}^3 \\ T_1 &= 20^\circ\text{C} \\ &= 20 + 273 \\ &= 293 \text{ K} \\ T_2 &= 90^\circ\text{C} = 90 + 273 = 363 \text{ K} \end{aligned}$$

First, you need to calculate V_2 :

$$\begin{aligned} \frac{V_1}{T_1} &= \frac{V_2}{T_2} \\ V_2 &= \frac{(V_1 T_2)}{T_1} \\ &= \frac{(0.015 \times 363)}{293} \\ &= 0.0186 \text{ m}^3 \end{aligned}$$

$$\begin{aligned} \Delta V &= V_2 - V_1 \\ &= 0.0186 - 0.015 \\ &= 3.6 \times 10^{-3} \text{ m}^3 \end{aligned}$$

$$\begin{aligned} W &= P\Delta V \\ &= 1.0 \times 10^5 \times 3.6 \times 10^{-3} \\ &= 360 \text{ J (2 s.f.)} \end{aligned}$$





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B. The particulate nature of matter / B.4 Thermodynamics (HL)

The first law of thermodynamics (HL)

B.4.1: First law of thermodynamics (HL) B.4.9: Isovolumetric, isobaric, isothermal and adiabatic processes (HL)

B.4.10: Adiabatic processes in monatomic ideal gases (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Understand and apply the first law of thermodynamics as given by $Q = \Delta U + W$.
- Understand isothermal, isovolumetric, isobaric and adiabatic processes.
- Use the equation $PV^{\frac{5}{3}} = \text{constant}$ to model an adiabatic process.

A fridge is in a sealed room on a very hot day (**Figure 1**). The fridge is powered by a power source outside the room. The walls of the room are perfectly insulated so that no heat transfers between the inside and the outside of the room.

What will happen if the fridge door is opened and left open? Will the room get warmer, get cooler or stay the same temperature? Click on 'Show or hide solution' to see the answer.

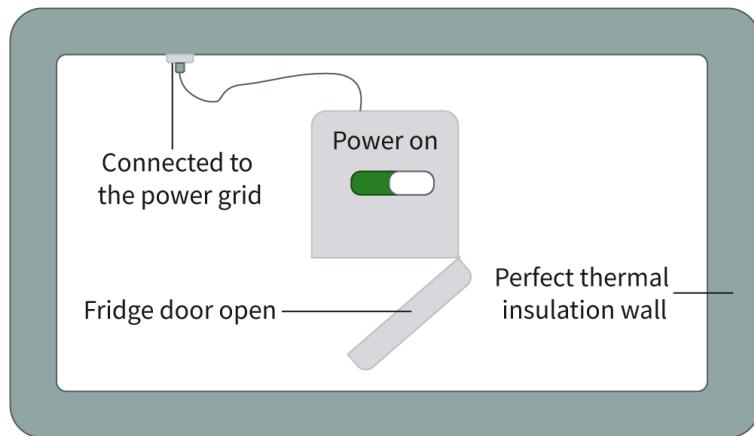


Figure 1. A fridge in a sealed room.

More information for figure 1

This illustration depicts a room with perfect thermal insulation. Inside the room, there is a fridge labeled "Power on" indicating it is connected to the power source. The fridge door is shown as open, with a label pointing to it. Another label indicates the room's "Perfect thermal insulation wall." A line connects the fridge to the "Connected to the power grid" label, suggesting that the fridge is operational due to the power connection. The image illustrates the scenario of an open fridge within a sealed environment to prompt the viewer to consider the thermodynamic consequences.

Student view



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The answer is that the temperature of the room increases. Electrical energy is entering the room and thermal energy can't leave the room, so the total energy inside the room is increasing.

When the fridge door is opened, the interior of the fridge gets warmer. When the fridge tries to cool the air inside, it must 'extract' the thermal energy from this air and transfer it somewhere else. There are radiators at the back of a fridge releasing heat to the air. The fridge emits more heat from these pipes than is removed from the interior of the fridge, so the room heats up.

The first law of thermodynamics

The first law of thermodynamics is an application of the principle of conservation of energy ([subtopic A.3 \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43083/\)](#)):

Energy can neither be created nor destroyed. It can only be transferred from one form to another.

More specifically, the law can be written as:

The thermal energy, Q , entering a closed system is equal to the sum of the change in internal energy, ΔU , of the system and the work done, W , by the system.

This is mathematically expressed by the equation in **Table 1**.

Table 1. Equation for thermal energy.

Equation	Symbols	Units
$Q = \Delta U + W$	Q = thermal energy	joules (J)
	ΔU = change in internal energy	joules (J)
	W = work done	joules (J)

Table 2 shows the sign conventions used in applying the first law of thermodynamics.

Table 2. Sign conventions used in applying the first law of thermodynamics.

	Q	ΔU	W
Positive	Thermal energy supplied to the system	Increase in internal energy of the system	Work done by the gas
Negative	Thermal energy removed from the system	Decrease in internal energy of the system	Work done on the gas

Note the following:

- Thermal energy Q is transferred between the system and its surroundings from high temperature to low temperature ([subtopic B.1 \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43777/\)](#)).
- The internal energy U of an ideal monatomic gas is the kinetic energy of the particles, which is described by the equation $U = \frac{3}{2}nRT$. For an ideal monatomic gas with fixed mass, internal energy is proportional to temperature ([subtopic B.3 \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44289/\)](#) and [section B.4.1 \(/study/app/math-aa-hl/sid-423-cid-762593/book/internal-energy-and-work-done-hl-id-44322/\)](#)).
- Work done W can be calculated by $W = P\Delta V$, given that pressure is constant ([section B.4.1 \(/study/app/math-aa-hl/sid-423-cid-762593/book/internal-energy-and-work-done-hl-id-44322/\)](#)).

Worked example 1

75 J of work is done on an ideal gas when it is compressed. If its internal energy decreases by 14 J, determine the thermal energy removed from the gas.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	Using the sign conventions in Table 2 : $W = -75 \text{ J}$ $\Delta U = -14 \text{ J}$
Step 2: Write out the equation.	$Q = \Delta U + W$
Step 3: Substitute the values given.	$= -14 + (-75)$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= -89 \text{ J} \text{ (2 s.f.)}$ The negative value of Q means that 89 J of thermal energy has been removed from the gas.

Worked example 2

An ideal gas of volume 0.020 m^3 expands to a volume 0.025 m^3 at constant pressure of $1.1 \times 10^5 \text{ Pa}$ by absorbing $9.0 \times 10^3 \text{ J}$ of thermal energy. Determine the change in the internal energy of the gas.



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Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$V_1 = 0.020 \text{ m}^3$ $V_2 = 0.025 \text{ m}^3$ $\Delta V = 0.025 - 0.020$ $= 5.0 \times 10^{-3} \text{ m}^3$ $P = 1.1 \times 10^5 \text{ Pa}$ $Q = 9.0 \times 10^3 \text{ J}$
Step 2: Calculate the work done by the gas as it expands.	$W = P\Delta V$ $= 1.1 \times 10^5 \times 5.0 \times 10^{-3}$ $= 550 \text{ J}$
Step 3: Write out the equation and rearrange to make ΔU the subject.	$Q = \Delta U + W$ $\Delta U = Q - W$
Step 4: Substitute the values given.	$= 9.0 \times 10^3 - 550$
Step 5: State the answer with appropriate units and the number of significant figures used in rounding.	$= 8450 \text{ J}$ $= 8500 \text{ J} \text{ (2 s.f.)}$

Section

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Feedback

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 ΔU has a positive sign, meaning that the internal energy of the gas has increased.

Assign

The four thermodynamic processes

There are four physical quantities involved in the first law of thermodynamics:

- **Temperature** (relating to internal energy)
- **Pressure and volume** (relating to work done)
- **Heat** (thermal energy added to or removed from the system)

There are four thermodynamic processes. In each process, one of the quantities remains constant.

Isothermal process

During an isothermal process, **temperature remains constant**. This means that the internal energy remains constant. The system must be in contact with the surroundings, and the process must take place slowly to ensure that thermal equilibrium between the system and the surroundings is maintained.

If the temperature remains constant, then the internal energy remains constant so $\Delta U = 0$:

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$$\begin{aligned} Q &= \Delta U + W \\ &= 0 + W \end{aligned}$$

$$Q = W$$

- The thermal energy supplied to the system is equal to the work done **by** the system.
- The thermal energy removed from the system is equal to the work done **on** the system.

For example, during the phase change of condensation, water vapour turns into liquid water. Energy is transferred to the surroundings during the phase change, but the temperature remains the same ([subtopic B.1 \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43777/\)](#)).

Isovolumetric process

During an isovolumetric process, **volume remains constant**. This means that no work is done on or by the system as ΔV is zero: $W = 0$

$$\begin{aligned} Q &= \Delta U + W \\ &= \Delta U + 0 \end{aligned}$$

$$Q = \Delta U$$

- Supplying thermal energy to the system causes the internal energy to increase (by the same amount) and the temperature will increase.
- Removing thermal energy from the system causes the internal energy to decrease and the temperature will decrease.

For example, if water is heated in a pan with a lid on a stove, the stove supplies thermal energy to the water. The volume of the water doesn't change as it is a closed system. Therefore, the internal energy of the water will increase and the temperature of the water will increase.

Isobaric process

During an isobaric process, **pressure remains constant**. **Figure 2** shows the work done by a gas.

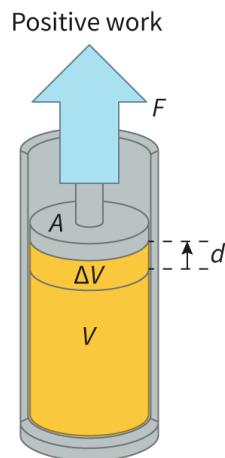


Figure 2. Work done by a gas.

[More information for figure 2](#)



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The diagram illustrates a cylindrical piston with a gas inside. The piston is shown in an upward motion indicating positive work. Several variables are labeled on the diagram: 'A' represents the area of the piston surface, 'F' is the force applied causing the upward movement, 'd' is the distance the piston has moved, ' ΔV ' indicates the change in volume, and 'V' is the volume of the gas. The diagram visually explains how work is done by the gas when the piston moves upward under constant pressure, expanding the volume.

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The equation for work done is ([section B.4.1 \(/study/app/math-aa-hl/sid-423-cid-762593/book/internal-energy-and-work-done-hl-id-44322/\)](#)):

$$W = P\Delta V$$

If ΔV is not zero, then W is also not zero. Therefore, we must consider the whole equation for the first law of thermodynamics:

$$Q = \Delta U + W$$

For example, consider a gas in a container with a piston which is free to move. If the heat is quickly added to the gas (+ Q), two things could happen. The internal energy of the gas will increase (+ ΔU) and/or the piston will move as the gas expands (+ W).

Adiabatic process

During an adiabatic process, **no thermal energy is transferred between the system and its surroundings**: $Q = 0$. This can be achieved if the process happens quickly (there is no time for a thermal energy transfer) or the system is isolated (no heat can be transferred).

$$Q = \Delta U + W$$

$$0 = \Delta U + W$$

$$\Delta U = -W$$

For a gas:

- For an adiabatic expansion, W is positive so ΔU must be negative, and the temperature of the gas decreases.
- For an adiabatic compression, W is negative so ΔU must be positive, and the temperature of the gas increases.

For example, the adiabatic process explains why deodorant cans feel cool to the touch. As the gas leaves the can, the remaining gas inside the canister expands, doing work. If this expansion happens quickly, the expansion is adiabatic, as heat does not have time to enter the can. This means the positive work done by the can is equal to the (negative) change in internal energy, and the temperature of the gas inside the can decreases.



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Watch **Video 1** to see a demonstration of adiabatic heating.

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Adiabatic Heating Demo



Video 1. A demonstration of change in internal energy due to an adiabatic process.

What are the signs of Q , ΔU and W in the demonstration in **Video 1**? Click ‘Show or hide solution’ to see the answer.

No thermal energy is transferred between the system and its surroundings, so: $\Delta Q = 0$

As the air is compressed, W is negative. Then, according to $Q = \Delta U + W$, ΔU must be positive.

For a fixed quantity of a monatomic ideal gas, when its state changes adiabatically from pressure P_1 and volume V_1 to pressure P_2 and volume V_2 , the following relationship is found:

$$P_1 V_1^{\frac{5}{3}} = P_2 V_2^{\frac{5}{3}}$$

In other words, this can be expressed by the equation in **Table 3**.

Table 3. Pressure-volume equation.

Equation	Symbols	Units
$PV^{\frac{5}{3}} = \text{constant}$	P = pressure	pascals (Pa)
	V = volume	cubic metres (m^3)

Table 4 shows a summary of the four thermodynamic processes.

Table 4. A summary of the four thermodynamic processes.

Thermodynamic process	Definition	After applying the first law of thermodynamics, the equation becomes
Isothermal	Temperature stays constant	$Q = W$

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Thermodynamic process	Definition	After applying the first law of thermodynamics, the equation becomes
Isovolumetric	Volume stays constant	$Q = \Delta U$
Isobaric	Pressure stays constant	$Q = \Delta U + W$
Adiabatic	No heat enters or leaves the system	$\Delta U = -W$

Study skills

The equation $P_1 V_1^{\frac{5}{3}} = P_2 V_2^{\frac{5}{3}}$ appears to ‘contradict’ the equation $P_1 V_1 = P_2 V_2$ ([subtopic B.3 \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44289/\)](#)).

Equation	When is it applicable?	
	Heat transfer, Q	Change of internal energy, ΔU
$P_1 V_1^{\frac{5}{3}} = P_2 V_2^{\frac{5}{3}}$	$Q = 0$	$\Delta U \neq 0$
$P_1 V_1 = P_2 V_2$	$Q \neq 0$	$\Delta U = 0$

This means that for the first (adiabatic) equation, the temperature is not constant, whereas for the second (non-adiabatic) equation the temperature is constant.

The derivation of the adiabatic process equation for a monatomic ideal gas

$P_1 V_1^{\frac{5}{3}} = P_2 V_2^{\frac{5}{3}}$ is beyond the scope of your DP physics course.

Note that in all circumstances the ideal gas law $PV = nRT$ still applies.

Worked example 3

A monatomic ideal gas doubles in volume during an adiabatic expansion. Determine the factor of the pressure change.

Solution steps	Calculations
Step 1: Write out the equation.	$P_1 V_1^{\frac{5}{3}} = P_2 V_2^{\frac{5}{3}}$



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Solution steps	Calculations
Step 2: Substitute the values given.	$V_2 = 2V_1$ $P_2 = \frac{P_1 V_1^{\left(\frac{5}{3}\right)}}{(2V_1)^{\left(\frac{5}{3}\right)}}$ $P_2 = \frac{P_1}{2^{\left(\frac{5}{3}\right)}}$
Step 3: State the answer with appropriate units and the number of significant figures used in rounding.	$P_2 = 0.31P_1$

PV diagrams

The four thermodynamics processes can be shown on pressure–volume (*PV*) diagrams with pressure on the *y*-axis and volume on the *x*-axis.

In an isobaric process, the pressure is constant. On a *PV* diagram, this is shown as a **horizontal line** (**Figure 3**).

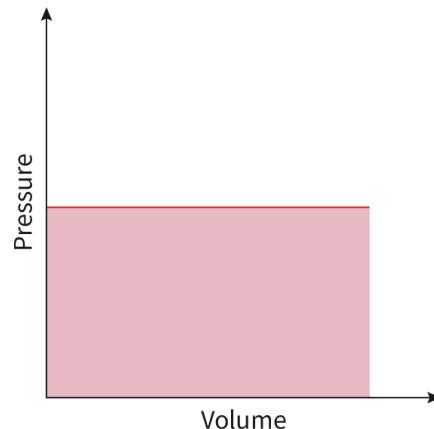


Figure 3. A PV diagram of an isobaric process.

More information for figure 3

The image is a PV (Pressure-Volume) diagram illustrating an isobaric process, where pressure remains constant. The X-axis is labeled "Volume," and the Y-axis is labeled "Pressure." The graph depicts a horizontal line, indicating that pressure does not change with varying volume. Below this line, a shaded area represents work done during the process. This visual setup clearly shows how the isobaric process is characterized by constant pressure, emphasizing the work done as the area under the line.

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The work done on or by a gas is $W = P\Delta V$ ([section B.4.1 \(/study/app/math-aa-hl/sid-423-cid-762593/book/internal-energy-and-work-done-hl-id-44322/\)](#)). This means that the shaded area under the line on a PV diagram represents work done.

Concept

The work done on or by a system during a thermodynamic process is equal to the area under the line on a PV diagram.

Figure 4 shows two isobaric processes, from A to B and from B to A. Although the area (work done) under each line is the same, W_1 is the work done by the gas (positive W , as the gas is expanding), while W_2 is the work done on the gas (negative W , as the gas is contracting).

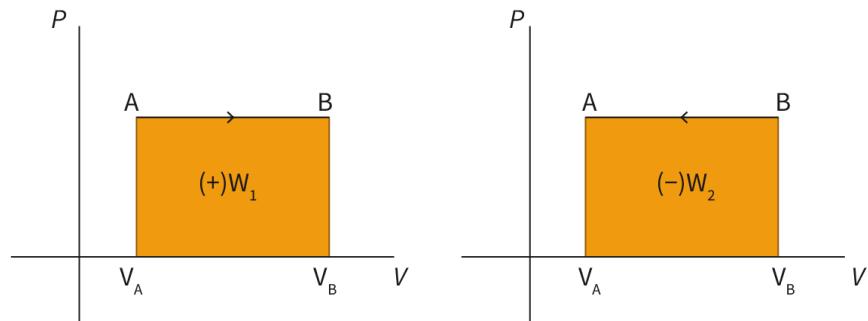


Figure 4. Two isobaric processes showing positive and negative work done.

 More information for figure 4

The image contains two separate graphs, both illustrating isobaric processes. Each graph depicts a rectangle on a pressure-volume (P-V) diagram.

On the left graph: - The X-axis represents volume (V) with labeled points V_A and V_B . - The Y-axis represents pressure (P). - The process moves from point A to point B with an arrow indicating the direction, and the interior of the rectangle is labeled ' $(+W_1)$ ' representing positive work done by gas expansion.

On the right graph: - The X-axis is similarly labeled with V_A and V_B . - The Y-axis remains for pressure (P). - The process moves from point B to point A, indicated by an arrow in the opposite direction, with a label ' $(-W_2)$ ' inside the rectangle, indicating negative work done on the gas by compression.

The area of both rectangles is equivalent, highlighting the work done during expansion and contraction.

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⌚ Making connections

- Ideal gas law ([subtopic B.3 \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44289/\)](#))
- Work done ([section B.4.1 \(/study/app/math-aa-hl/sid-423-cid-762593/book/internal-energy-and-work-done-hl-id-44322/\)](#))

The volume of a gas in an isovolumetric process is constant. This is shown as a **vertical line** on a *PV* diagram (**Figure 5**). The area under the line is zero, which indicates the work done is zero.

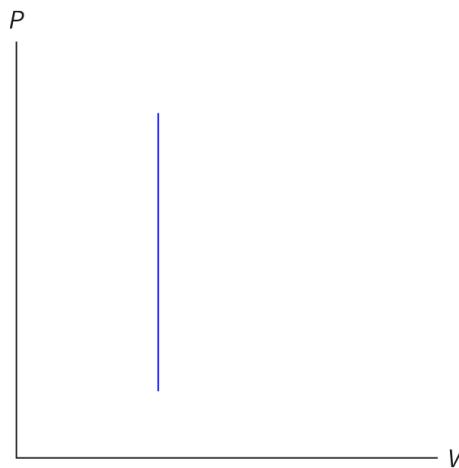


Figure 5. A PV diagram of an isovolumetric process.

🔗 More information for figure 5

The image is a PV diagram, which illustrates a process where the volume of a gas remains constant. This is represented by a vertical blue line on the diagram. The X-axis is labeled 'V' for volume, and the Y-axis is labeled 'P' for pressure. The vertical line suggests that as pressure changes, the volume does not, indicating an isovolumetric process. There are no values given on the axes, but the diagram visually communicates that there is no area under this line, signifying that no work is done during this process.

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In an isothermal process, the temperature is constant. This is shown as a curve on a *PV* diagram (**Figure 6**).

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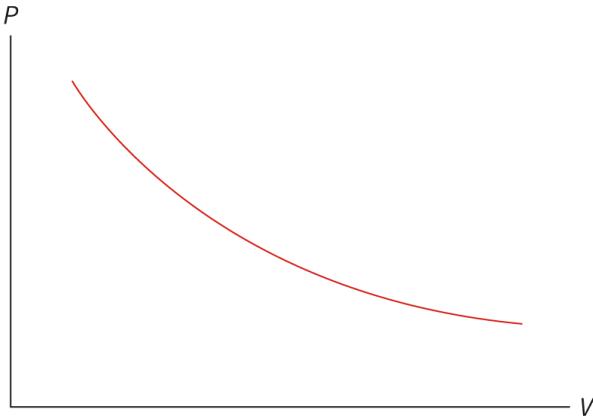


Figure 6. A PV diagram of an isothermal process.

More information for figure 6

The image depicts a PV diagram illustrating an isothermal process. The diagram features two axes: the vertical axis represents pressure (P) and the horizontal axis represents volume (V). The pressure axis is labeled with intervals from 0 to 1000 in increments of 200, while the volume axis is labeled from 0 to 70 at intervals of 10. A downward-sloping red curve is plotted on the graph, starting from a high pressure, low volume point and descending to a lower pressure, higher volume point. This curve represents an isothermal process, where temperature remains constant, aligned with the principles of the ideal gas law.

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The shape of the curve can be deduced by considering the ideal gas law ([subtopic B.3](#) (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44289/)):

$$PV = nRT$$

During an isothermal process, T is constant:

$$PV = \text{constant}$$

So:

$$P \propto \frac{1}{V}$$

Therefore, pressure is inversely proportional to volume.

Variations in pressure and volume will result in a change in temperature, unless the process is happening along an isothermal line. **Figure 7** shows the curves of an ideal gas at three different constant temperatures on a PV diagram. These curves are rectangular hyperbola.



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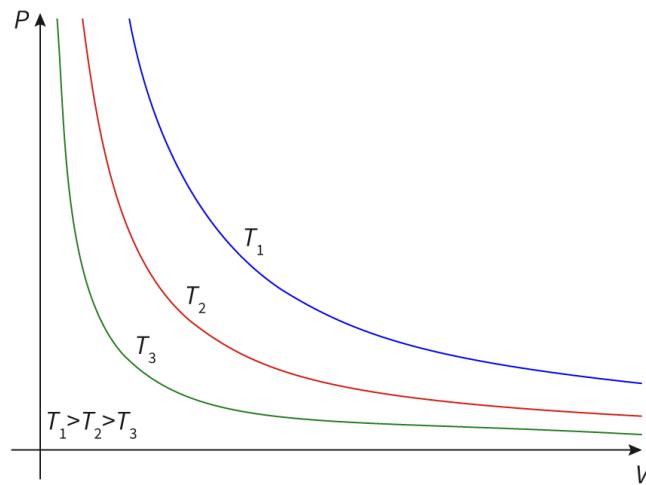


Figure 7. The curves of an ideal gas at three different constant temperatures.

More information for figure 7

The image is a graph illustrating the behavior of an ideal gas on a pressure-volume (PV) diagram at three different constant temperatures, labeled (T_1), (T_2), and (T_3), with ($T_1 > T_2 > T_3$). Each temperature is represented by a separate curve on the graph, which are rectangular hyperbolas.

- **X-axis:** This axis represents the volume ((V)), but specific units or markers are not visible.
- **Y-axis:** This axis represents the pressure ((P)), without specific units or markers.

The three curves all start on the Y-axis at different pressure levels but curve similarly as they move towards the X-axis. The highest temperature curve, (T_1), is at the top, followed by (T_2), and the lowest temperature curve, (T_3), is at the bottom, illustrating that higher temperature results in higher pressure for the same volume.

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How can we determine which isothermal curve has a higher or lower temperature? Click on the ‘Show or hide solution’ button to see the answer.

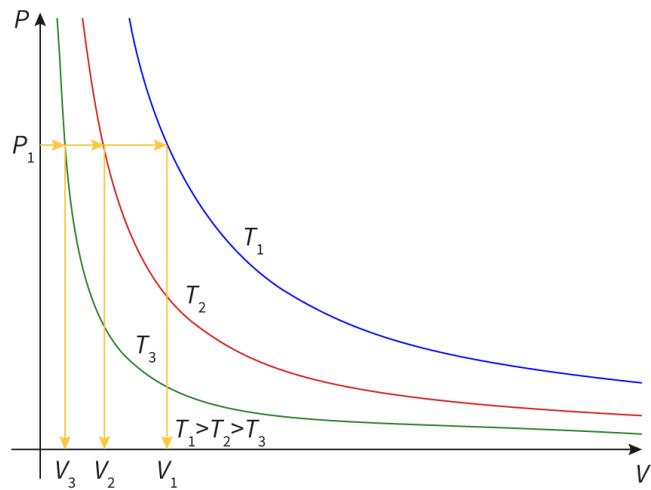
For isothermal curves on a PV diagram, the one further away from the origin has a higher temperature. This can be understood by looking at the ideal gas law again: $PV = nRT$

If temperature T is higher, the product of PV is greater. Hence, $T_1 > T_2 > T_3$ in the PV diagram.



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For an isothermal process, calculating the area under the curve (work done) is complicated. In DP physics, you will only be expected to estimate the area by counting squares (**Figure 8**).

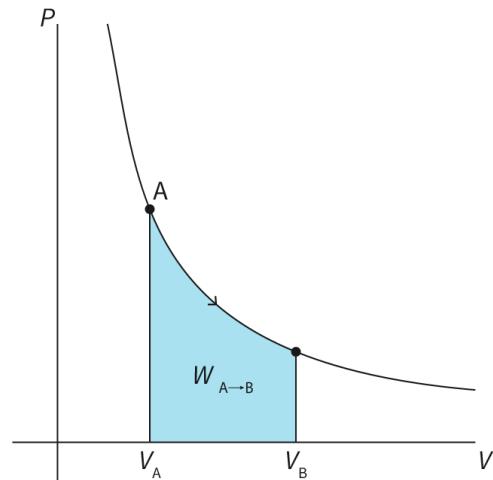


Figure 8. Estimating the work done.

🔗 More information for figure 8

The image is a graph illustrating the work done as the area under a curve representing an isothermal process. The X-axis is labeled as 'V' representing volume, with points marked as V_A and V_B . The Y-axis is labeled as 'P' representing pressure. There is a curved line starting from point A, moving downwards and curving to the right, ending at point B. Underneath this curve, the area is shaded in light blue indicating the work done ($W_{A \rightarrow B}$) between points A and B. The work done is described as the integral of P over volume change from V_A to V_B , represented graphically by the shaded area under the curve. The points A and B are marked on the curve, indicating starting and ending points.

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Figure 9 shows the four thermodynamic processes for the expansion of a gas.



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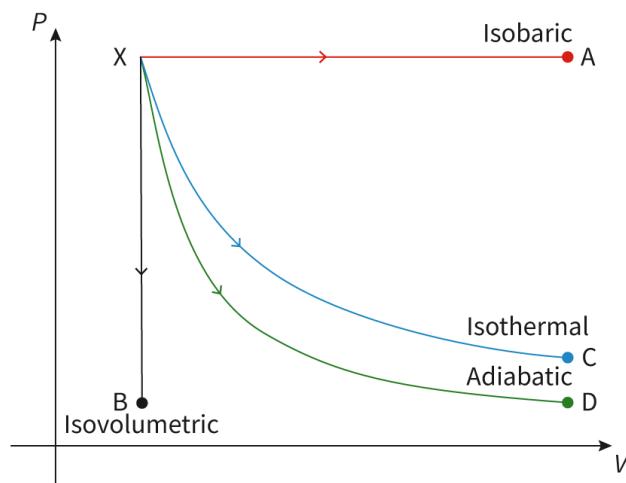


Figure 9. A PV diagram showing isobaric, isovolumetric, isothermal and adiabatic processes.

[More information for figure 9](#)

The image is a PV diagram illustrating four thermodynamic processes. The X-axis represents volume (V), and the Y-axis represents pressure (P). There are four distinct curves, each representing a different process: isobaric, isovolumetric, isothermal, and adiabatic.

1. **Isobaric Process:** Represented by a horizontal red line from point X to point A, indicating a process occurring at constant pressure.
2. **Isovolumetric Process:** Indicated by a vertical black line from point X to point B, representing a process at constant volume.
3. **Isothermal Process:** Shown as a blue curved line from point X to point C. This curve signifies a process at constant temperature, where the pressure decreases as volume increases.
4. **Adiabatic Process:** Depicted by a green curved line from point X to point D, slightly below the isothermal curve. This process involves no heat exchange, showing a decrease in pressure more pronounced than in the isothermal process as the volume increases.

Labels and arrows indicate the direction of each process, and points A, B, C, and D mark specific states within the diagram. The isothermal and adiabatic curves appear similar, but key differences in their gradients are noted.

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The curves for isothermal and adiabatic processes are very similar. In **Figure 9**, the initial temperature is the same for both processes. Both processes increase the volume of the gas to the same volume.

In adiabatic expansion, the temperature decreases, while in isothermal expansion, the temperature is constant. The final pressure after the adiabatic expansion will be lower than the final pressure after the isothermal expansion (**Figure 10**). Hence, the adiabatic curve is steeper than the isothermal curve.



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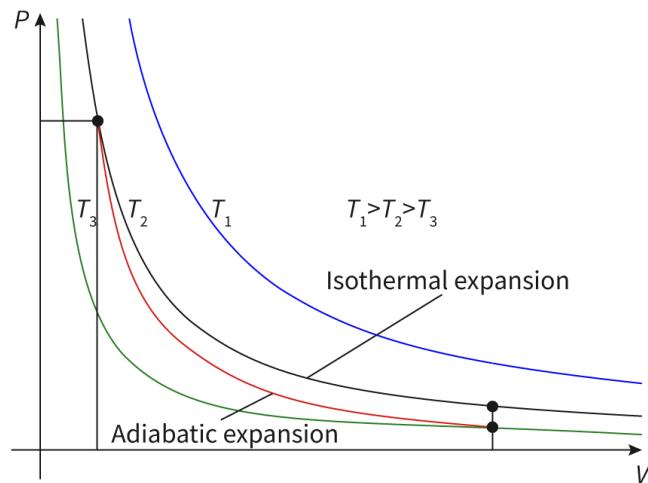


Figure 10. A PV diagram of isothermal and adiabatic expansion.

More information for figure 10

The image is a PV (Pressure-Volume) diagram comparing isothermal and adiabatic expansions. The vertical axis represents pressure (P) and the horizontal axis represents volume (V). There are two main curves depicted: one for isothermal expansion and another for adiabatic expansion.

1. Isothermal Expansion:

2. Shown as a curve extending downward and to the right, depicted with blue.
3. The curve is less steep compared to the adiabatic expansion.
4. The temperature is constant along this curve at various levels (T_1, T_2, T_3) with $T_1 > T_2 > T_3$.

5. Adiabatic Expansion:

6. Shown as a steeper curve than the isothermal one, depicted with green.
7. The temperature decreases along this curve.

The diagram visually illustrates that during adiabatic expansion, the pressure drops more rapidly with volume increase compared to isothermal expansion. Numeric temperature values (T_1, T_2, T_3) are indicated along the curves with T_1 being the highest and T_3 the lowest temperature for isothermal lines.

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We have compared adiabatic expansion and isothermal expansion. What happens during adiabatic compression and isothermal compression?

In adiabatic compression, the temperature increases, while in isothermal compression, the temperature is constant. The final pressure after the adiabatic compression is greater than the final pressure after the isothermal compression (**Figure 11**). Hence, the adiabatic curve is steeper than the isothermal curve.



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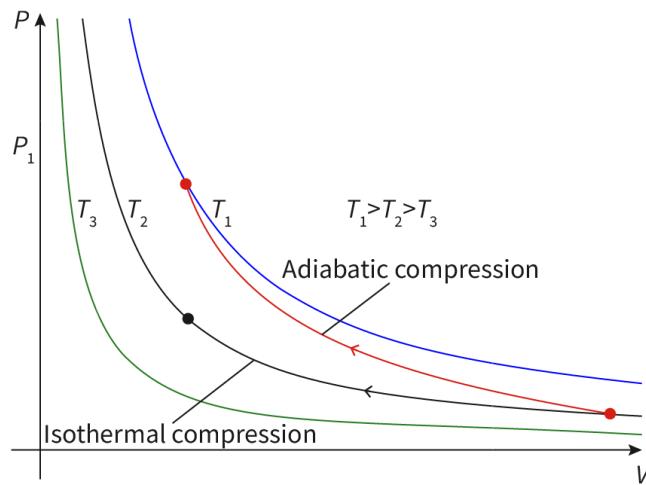


Figure 11. PV diagram of isothermal and adiabatic compression.

More information for figure 11

The image is a graph known as a PV diagram that depicts the relationship between pressure (P) and volume (V) during isothermal and adiabatic compression processes. The Y-axis represents pressure (P) and the X-axis represents volume (V). There are three curves shown on the graph. The green curve labeled 'Isothermal compression' represents the isothermal process, where temperature remains constant. The blue and red curves represent the adiabatic process, labeled 'Adiabatic compression,' where the temperature increases during compression. The adiabatic curve is steeper than the isothermal curve. The temperatures are labeled T₁, T₂, and T₃, with T₁>T₂>T₃, indicating that the temperature decreases down the adiabatic curve. Points on the curves are marked to show different states of compression, with the final pressure of the adiabatic compression being higher than that of the isothermal compression.

[Generated by AI]

The equation describing the adiabatic process is:

$$P_1 V_1^{\frac{5}{3}} = P_2 V_2^{\frac{5}{3}}$$

For the isothermal process, the ideal gas law states:

$$PV = nRT$$

and since temperature T is constant:

$$P_1 V_1 = P_2 V_2$$

By comparing the expressions for the adiabatic process and the isothermal process, we can see that the curved line for an adiabatic process will always be steeper than the curved line for an isothermal process, due to the $\frac{5}{3}$ power term.

Worked example 4

The pressure-volume graph for an ideal gas is shown in **Figure 12**. Identify whether work is being done on, or by, the gas, and calculate the work done.



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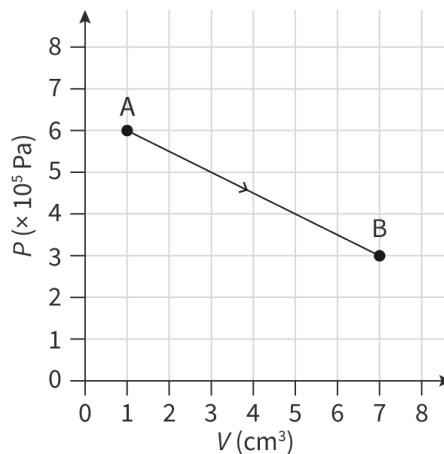


Figure 12. Pressure-volume graph for an ideal gas.

More information for figure 12

The graph is a pressure-volume diagram for an ideal gas, with the X-axis labeled as volume (V) in cubic centimeters (cm^3) ranging from 0 to 8, and the Y-axis labeled as pressure (P) in Pascals ($\times 10^5 \text{ Pa}$) ranging from 0 to 8. A straight line connects point A at $(1 \text{ cm}^3, 6 \times 10^5 \text{ Pa})$ to point B at $(7 \text{ cm}^3, 3 \times 10^5 \text{ Pa})$. The line slopes downward from left to right, indicating a decrease in pressure as volume increases. An arrow on the line shows the process direction from point A to point B.

[Generated by AI]

As the volume is increasing, (positive) work is being done by the gas.

The work done is the area under the line on the PV diagram:

$$\begin{aligned} W &= \frac{1}{2} \times (3 \times 10^5 \times 6 \times 10^{-6}) + (3 \times 10^5 \times 6 \times 10^{-6}) \\ &= 0.9 + 1.8 \\ &= 2.7 \text{ J} \end{aligned}$$

Work through the activity to check your understanding of the first law of thermodynamics and the four thermodynamic processes.

5 section questions ^

Question 1

HL Difficulty:

A gas expands and transfers 130 kJ of heat to the surroundings. The work done is 70 kJ. Determine the change in internal energy.

1 -200 kJ



2 +200 kJ

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3 +60 kJ

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Explanation

Work is done by the gas, so W is positive:

$$W = 70 \text{ kJ}$$

Heat is given out by the gas, so Q is negative:

$$Q = -130 \text{ kJ}$$

$$Q = \Delta U + W$$

$$\begin{aligned}\Delta U &= Q - W \\ &= -130 - 70 \\ &= -200 \text{ kJ}\end{aligned}$$

The negative sign shows that the internal energy of the gas decreases.

Question 2

HL Difficulty:

In a thermodynamic process, 345 kJ of heat is supplied to a gas and its internal energy increases by 427 kJ. Determine the work done during this process.

1 -82 kJ, the work is done on the gas. ✓

2 -770 kJ, the work is done on the gas.

3 +770 kJ, the work is done by the gas.

4 +82 kJ, the work is done by the gas.

Explanation

$$Q = 345 \text{ kJ}$$

$$\Delta U = 427 \text{ kJ}$$

$$Q = \Delta U + W$$

$$\begin{aligned}W &= Q - \Delta U \\ &= 345 - 427 \\ &= -82 \text{ kJ (2 s.f.)}\end{aligned}$$

W is negative, meaning that work is done on the gas.



**Question 3**

HL Difficulty:

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A monatomic ideal gas expands adiabatically from $2.0 \times 10^{-3} \text{ m}^3$ to $4.0 \times 10^{-3} \text{ m}^3$. The initial pressure is $8.0 \times 10^5 \text{ Pa}$. Calculate the new pressure of the gas.

1 $2.5 \times 10^5 \text{ Pa}$ ✓

2 $1.0 \times 10^5 \text{ Pa}$

3 $4.0 \times 10^5 \text{ Pa}$

4 $5.0 \times 10^5 \text{ Pa}$

Explanation

$$P_1 V_1^{\frac{5}{3}} = P_2 V_2^{\frac{5}{3}}$$

$$8.0 \times 10^5 \times (2.0 \times 10^{-3})^{\frac{5}{3}} = P_2 \times (4.0 \times 10^{-3})^{\frac{5}{3}}$$

$$P_2 = 2.5 \times 10^5 \text{ Pa} \text{ (2 s.f.)}$$

Question 4

HL Difficulty:

Two identical samples of gas are at the same volume, pressure and temperature. One sample is compressed isothermally from V_1 to V_2 so that work W_1 is done on it. The other gas is compressed adiabatically from V_1 to V_2 . State whether the work done on the second gas will be less than, equal to, or greater than W_1 .

1 Greater than W_1 ✓

2 Equal to W_1

3 Less than W_1

4 Cannot be determined from the information given

Explanation

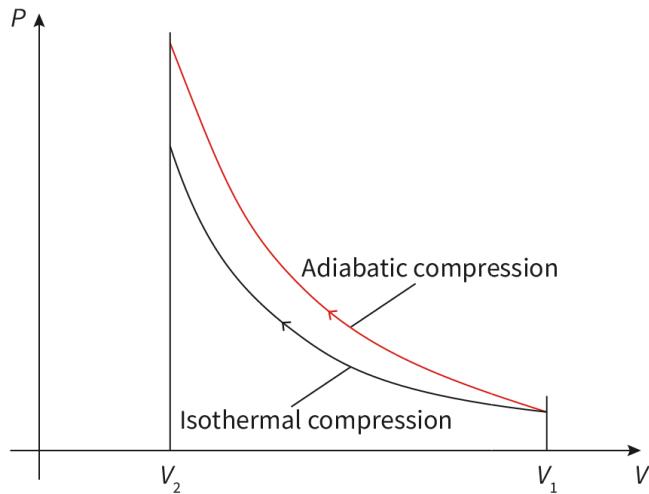
The curve of an adiabatic process is always steeper than the curve of an isothermal process.

Since work done is the area under the curve, the work done for an adiabatic compression is larger than the work done for an isothermal compression, therefore the work done is greater than W_1 .



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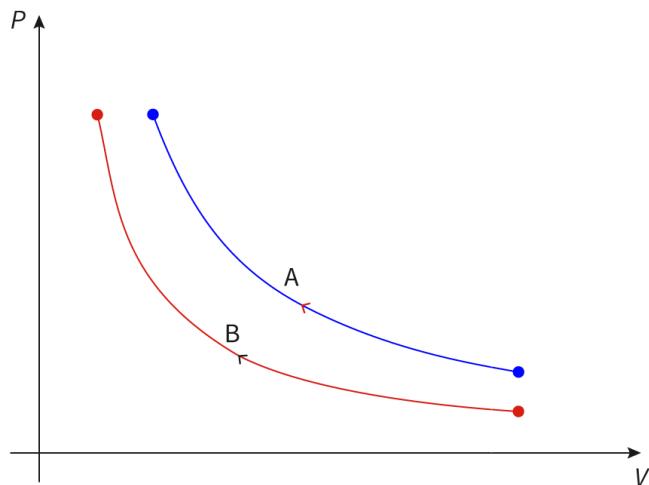


More information

Question 5

HL Difficulty:

Gases, A and B, each go through an isothermal process as shown in the PV diagram. Each gas has a fixed mass. Determine which gas has a higher internal energy.



More information

A



Accepted answers

A, a

Explanation

In a PV diagram, the further the curve of an isothermal process is from the origin, the higher the temperature. A is further from the origin. The internal energy U is proportional to temperature T for a fixed mass of gas according to $U = \frac{3}{2}nRT$, so gas A has a greater internal energy.



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B. The particulate nature of matter / B.4 Thermodynamics (HL)



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Activity: First law of thermodynamics and the four thermodynamic processes (HL)

B.4.1: First law of thermodynamics (HL) B.4.9: Isovolumetric, isobaric, isothermal and adiabatic processes (HL)

B.4.10: Adiabatic processes in monatomic ideal gases (HL)



ⓘ Teacher instructions

Note that this simulation does have some considerations for its use that could be used as discussion points in class.

- On the 'ideal' setting, the simulation **does not** calculate the work done for the moving container wall. This means that during any one of the ideal gas processes, there would be heat transfer. This is a value not given in the simulation.
- On the 'explore' setting, work done **is** calculated for the moving container wall based upon the particle collisions with the wall during the change in volume.

PhET issue teacher tips for each simulation which detail the exact working, and for this simulation they can be found on the PhET website [here ↗](https://phet.colorado.edu/services/download-servlet?filename=/teachers-guide/gas-properties-html-guide_en.pdf) (https://phet.colorado.edu/services/download-servlet?filename=/teachers-guide/gas-properties-html-guide_en.pdf) (may require you to login to

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Higher level (HL)

- **IB learner profile attribute:**
 - Inquirer
 - Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

Instructions:

Use the simulation to explore the four thermodynamic processes. Discuss what you see for each process.

Isothermal

1. Select 'Ideal'. Pump in the gas particles.
2. Select 'Temperature (T)' in the 'Hold Constant' box.
3. Change the volume by dragging the handle bar.

Isobaric

1. Select 'Ideal'. Pump in the gas particles.
2. Select 'Pressure $\uparrow\downarrow V$ ' in the 'Hold Constant' box.
3. Use the 'Heat' and 'Cool' slider to change the temperature of the gas.
4. Now, select 'Pressure $\uparrow\downarrow T$ ' in the 'Hold Constant' box.
5. Change the volume by dragging the handle bar.

Isovolumetric

1. Select 'Ideal'. Pump in the gas particles.
2. Select 'Volume (V)' in the 'Hold Constant' box.
3. Use the 'Heat' and 'Cool' slider to change the temperature of the gas.

Adiabatic

1. Refresh the page and then select 'Explore'. Pump in the gas particles and wait for the gas particles to settle.
2. Decrease the volume by dragging the handle bar to the right.



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B. The particulate nature of matter / B.4 Thermodynamics (HL)

Entropy and the second law of thermodynamics (HL)

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- B.4.4: Entropy (HL) B.4.5: Entropy determination (HL) B.4.6: Second law of thermodynamics (HL)
B.4.7: Irreversible processes in real isolated systems (HL) B.4.8: Local entropy decrease and surroundings entropy increase (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Understand that entropy is a measure of the amount of disorder of particles in a system, and how it can be determined.
- Understand that the second law of thermodynamics relates to the change in entropy of an isolated system and solve problems involving entropy changes.
- Understand entropy in real isolated systems and non-isolated systems.

Video 1 shows a domino rally, with a very ordered system of dominoes. Imagine you randomly threw dominoes on the floor. How probable would it be that the random configuration allowed a domino chain reaction? Why is it so difficult to build a system like this?

35,000 DOMINOES - Domino World 2019



Video 1. An ordered system of dominoes.

More information for video 1

The video presents an elaborate and captivating demonstration of a large-scale domino and chain reaction setup, offering a visual exploration of cause and effect, energy transfer, and the concept of ordered systems. It begins with vibrant, slightly blurred footage of meticulously arranged domino patterns on a carpeted floor. The dominoes come in a variety of forms, including traditional flat pieces and more complex, interlocking 3D designs, highlighting not only the diversity of materials used but also the level of precision required to assemble such a delicate system. The camera pans slowly to emphasize the intricate artistry and engineering behind the layouts.

The scene transitions to a dynamic K'NEX structure, featuring small balls rolling down colorful plastic tracks interwoven with

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materials like wood and styrofoam cups. This combination of components showcases the builders' creativity in constructing a chain reaction system that relies on multiple physical principles, such as gravitational potential energy, momentum, and mechanical interactions. Each transition from one part of the system to the next is seamless and deliberate, underscoring the careful planning and alignment required to sustain the chain reaction without interruption.

The camera reveals large-scale domino artwork on the floor, including a rocket in space and the text "Lake Trust Credit Union," representing both functional and aesthetic aspects of the setup. The inclusion of labeled structures, such as "Ann Arbor Hands-On Museum," further reinforces the event's educational and community-driven goals.

The chain reaction is then initiated by a boy standing beside a K'NEX setup, enclosed by a yellow safety barrier. Viewers observe as ping pong balls travel along orange tracks, activating levers, gears, and spinning mechanisms. These actions demonstrate the transfer of energy from one object to another through motion and force.

The reaction progresses to the domino floor setups, where patterns and structures—ranging from spirals and curves to towers and 3D shapes—topple in mesmerizing succession. The collapse of the "Ann Arbor Hands-On Museum" structure signifies a key milestone in the sequence, while the fall of a massive, multicolored spiral delivers a visually dramatic moment that accentuates the builders' precision and spatial awareness. Strings and tension-based triggers add suspense, illustrating mechanical principles such as tension release and gravity-driven motion.

As the chain reaction loops back to K'NEX components, viewers witness more balls rolling along tracks, maintaining the system's momentum until a final collapse is triggered. The sequence ends with a towering, rainbow-colored domino structure falling in a powerful visual crescendo. The camera slowly pans across the room to show the aftermath—a scattered field of fallen dominoes and dismantled structures, symbolizing the conclusion of an extraordinary, interconnected event.

Figure 1 shows four systems. How easy would it be to return each system to its initial state?

Section

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Assign



Figure 1. Can these systems be returned to their original states?

More information for figure 1

The image contains four distinct pictures organized in a grid layout:

1. **Top Left:** A photograph of playing cards scattered across a green surface. The cards show various suits and numbers, seemingly placed randomly.
2. **Top Right:** A photograph of a snooker table setup. Red balls are clustered together, a black ball is visible in front, and yellow, green, and blue balls are positioned around the table.
3. **Bottom Left:** A photograph showing milk being poured into a cup of tea, creating a swirling pattern as the two liquids mix.

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4. Bottom Right: A photograph of a raw egg cracked open with its contents spilled onto a flat surface, displaying both the yolk and eggshell fragments.

[Generated by AI]

In each case, disorder is being introduced to the system. In some cases, like the playing cards and the snooker balls, it is possible to return the system to its original state. With the mixing of the tea and the milk, and the broken egg, the disorder is much harder to undo.

What do you think is most common in nature – order or disorder?

Entropy

Physicists have a way of quantifying disorder. It is called entropy. Entropy is a measure of the amount of disorder of the particles in a system.

Look at **Figure 2**. It shows a tidy bedroom and a messy bedroom. Which bedroom has greater entropy?



Figure 2. Which bedroom has greater entropy?



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In one room, there is a high level of disorder. Clothes and toys are spread all over the room. It is very hard to predict where individual items might be, and there are few patterns to help us make predictions to find, for example, a pair of socks. The room has high disorder, so high entropy.

In the other room, everything is very tidy, predictable and ordered. The level of disorder is low, and so the level of entropy is low.

The concept of order and disorder can be applied to many different physical systems. For example, a gas is a more disordered or less ordered phase of matter than a liquid. In a gas, the particles move freely and randomly, while in a liquid, the bonds between the particles restrict their movement. We say that the gas has more disorder, and a higher entropy. A solid is a more ordered state of matter than a liquid. This is because, in a solid, the particles are fixed in their lattice positions, and only have a small vibrational motion. We say that the liquid has more entropy than the solid.

Theory of Knowledge

Entropy applies to every part of our lives. Indeed, everything seems to tend to chaos. For example, our rooms inevitably become cluttered with time or divergent behaviours in societies quickly escalate. Can you think of other examples of daily situations that tend to chaos and entropy increase?

Creativity, activity, service

Strand: Creativity

Learning outcome: Demonstrate that challenges have been undertaken, developing new skills in the process

Scientific concepts such as ‘entropy’ that have broad implications about the nature of our universe often capture the imagination of artists. Many artists have taken inspiration from the concept of entropy. This image in [this link](https://www.tate.org.uk/art/art-terms/e/entropy) (https://www.tate.org.uk/art/art-terms/e/entropy) features the work of Larry Bell and his interpretation on the second law of thermodynamics.

Can you find any other examples of visual art, music or poetry that convey the theme of entropy?

If we raise the temperature of a substance, then the average kinetic energy of its particles increases. This increases the disorder of the system. Similarly, a fixed quantity of gas occupying a large volume is more disordered than the same quantity of gas in a small volume. In the large volume, we know less about the position of the individual gas particles.



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Concept

Entropy (S) is defined as a thermodynamic quantity that relates to the degree of disorder of the particles in a system.

In 1877, the Austrian physicist Ludwig Boltzmann established a way to evaluate entropy, quantitatively. Entropy is related to the properties of the individual particles in the system. It is a measure of the number of possible microstates of the system. The term ‘microstate’ means a specific molecular configuration.

Assuming each microstate has the same probability, the entropy S is proportional to the natural logarithm of the number of microstates Ω . The proportionality constant is the Boltzmann constant, k_B .

It can be written mathematically as the equation in **Table 1**.

Table 1. Equation for entropy.

Equation	Symbols	Units
$S = k_B \ln \Omega$	S = entropy	joules per kelvin ($J K^{-1}$)
	k_B = Boltzmann constant, $1.38 \times 10^{-23} J K^{-1}$	Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet
	Ω = number of microstates	

Try flipping the 5 coins in **Interactive 1** by pressing ‘1 Flip’. This flips all the coins together. Do you think it is possible for them to all be heads? What combination are you likely to get?



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Interactive 1. Tossing coins.

More information for interactive 1

This interactive tool allows users to explore probability by flipping five virtual coins at once and tracking how many land on heads. A number line at the bottom, ranging from 0 to 8, represents the possible number of heads that can result from the flips. Above this number line, red numbers and lines indicate the frequency or count of each outcome (number of heads). Initially, all red numbers are zero since all the coins are in the tails position. As you flip the coins, these red numbers update to reflect how many times each specific number of heads has occurred. By observing how these numbers change over multiple flips, you can visualize probability concepts and the distribution of outcomes.

When the user flips the coins for the first time, the outcome is random. For example, if the result is HHTTT (two heads and three tails), the number line updates by placing 1 above the number 2, indicating that this outcome has occurred once. If the next flip results in HHHTT (three heads and two tails), 1 appears above the number 3 on the number line. Now, the display shows that two different outcomes have been observed—one instance of two heads and one instance of three heads.

If the user flips again and gets another outcome with two heads (such as HTTHH), the red number above 2 increases to 2, reflecting that this outcome has occurred twice. The more the user flips, the more the number line updates, showing which outcomes appear most frequently. Over multiple flips, users can observe patterns in the distribution of results, seeing that some outcomes appear more often than others.

This interactive helps users understand probability and randomness by visualizing how different outcomes accumulate over time. By flipping the coins multiple times, users can see how probability distributions take shape and recognize that, over many trials, some results are more common than others. This makes abstract probability concepts more concrete and engaging.

Table 2 shows the possible outcomes of flipping the coins.

Table 2. Macrostates and microstates of a system of 5 coins.



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Possible macrostates	Possible microstates	Number of microstates
5 heads, 0 tails	HHHHH	1
4 heads, 1 tail	HHHHT, HHHTH, HHTHH, HTHHH, THHHH	5
3 heads, 2 tails	HHHTT, HHTTH, HTTHH, TTHHH, HHTHT, HTHTH, THTHH, HTHHT, THHTH, THHHT	10
2 heads, 3 tails	TTTHH, TTHHT, THHTT, HHTTT, TTHTH, THTHT, HTHTT, THTTH, HTHTT, HTTTT	10
1 head, 4 tails	TTTTH, TTTHT, TTHTT, THTTT, HTTTT	5
0 heads, 5 tails	TTTTT	1
		Total = 32

- A microstate refers to a specific molecular configuration. In the coin example, a microstate is 'HTHTH' or 'THTHH'. There are 10 microstates for '3 heads, 2 tails' and each microstate has the same probability. For example, the probability of five heads is $\frac{1}{32}$. In a thermodynamic system, the microstates may be referring to the momentum or orientation of the particles, which can't be observed.
- A macrostate is a larger-scale, measurable outcome, resulting from the outcome of each of the smaller microstates. For example, 'HTHTH' and 'THTHH' represent the same macrostate. They both have two tails and three heads. It does not matter which three coins are heads and which two coins are tails. So in our coin example, there are only six macrostates in total. In a thermodynamic system, the macrostates may be pressure, temperature, etc., which are observable.

By counting the possible microstates of a macrostate, we can evaluate the probability of the macrostate, and therefore determine the entropy of the system. Referring to the 5-coin system above, disordered outcomes (3H2T or 3T2H) have many more possible microstates than ordered ones, and so are more likely to occur. These coin arrangements (3H2T or 3T2H) represent the most likely outcome (and the outcomes with the highest entropy).

Study skills

In DP physics, the microstates of a system will always be equally probable. They will be described using simple models (for example, tossing coins).

Worked example 1

Calculate the entropy of an isolated system containing 50 fair six-sided dice, in which the dice are:

- a) all rolled with the number 4

b) rolled for any number

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a)

Section	Solution steps	Calculations
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	Step 1: Determine the possible outcomes.	Since all the dice are rolled with the number 4, there is only one possible outcome: $\Omega = 1^{50} = 1$
	Step 2: Write out the equation.	$S = k_B \ln \Omega$
	Step 3: Substitute the values given.	$= (1.38 \times 10^{-23}) \ln 1$
	Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 0 \text{ J K}^{-1}$ The entropy is very low because this outcome is very unlikely to happen.

b)

Solution steps	Calculations
Step 1: Determine the possible outcomes.	Each die may be rolled as any number from 1 to 6, so the total possible outcomes (microstates) is: $\Omega = 6^{50} = 8.08 \times 10^{38}$
Step 2: Write out the equation.	$S = k_B \ln \Omega$
Step 3: Substitute the values given.	$= (1.38 \times 10^{-23}) \ln 8.08 \times 10^{38}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 1.24 \times 10^{-21} \text{ J K}^{-1} \text{ (3 s.f.)}$ The entropy of rolling all dice as 4 is smaller than rolling the dice with any numbers. The system is much more likely to evolve from having all dice as 4 (more ordered and low entropy) to having dice as any number (less ordered and high entropy).

This statistical view of entropy explains why entropy increases over time for any isolated system.

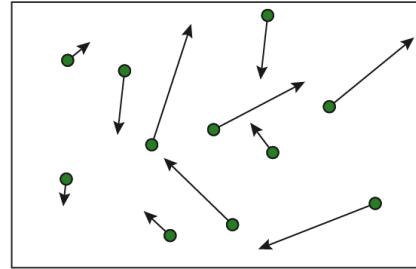


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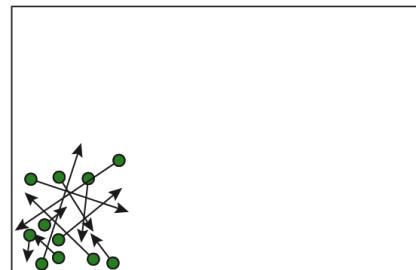
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For example, the probability of the air particles in a room spreading out (high entropy) is much higher than the probability of all the air particles clumping together in one corner (low entropy) (**Figure 3**). This explains why we usually observe the air particles spreading out in a room.

Note that it is wrong to claim that having all the particles clumped together in one corner is impossible, it is just that the chance is extremely small.



a) Likely (high entropy)



b) Highly unlikely (low entropy)

Figure 3. The probability of air particles (a) spreading out (higher entropy) is higher than the probability of air particles (b) clumping together (low entropy).

🔗 More information for figure 3

The image consists of two sections labeled (a) and (b). In section (a), labeled 'Likely (high entropy),' several green dots representing particles are dispersed throughout the space with arrows pointing in various directions, indicating movement. This illustrates a scenario where particles are spread out, showcasing a state of high entropy. In section (b), labeled 'Highly unlikely (low entropy),' all green dots are clustered together in one corner of the space, with arrows also clustered, indicating that particles are not dispersed. This demonstrates a state of low entropy where particles are clumped together, depicting a rare occurrence according to entropy principles.

[Generated by AI]

Entropy can also be defined in terms of macroscopic properties such as temperature and thermal energy as shown in **Table 3**.

Table 3. Equation for change in entropy.

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Equation	Symbols	Units
$\Delta S = \frac{\Delta Q}{T}$	ΔS = change in entropy	joules per kelvin ($J K^{-1}$)
	ΔQ = change in thermal energy	joules (J)
	T = temperature	kelvin (K)

Study skills

$\Delta S = \frac{\Delta Q}{T}$ is only valid for energy changes at a constant temperature, T .

- When thermal energy is added to a system, ΔQ is positive and ΔS is positive.
- When thermal energy is removed from a system, ΔQ is negative and ΔS is negative.

For example, when ice melts, thermal energy is added to the system, but the temperature of the ice remains constant. In ice, the water molecules are bound together in a regular crystal lattice. This represents a highly ordered state. The water molecules in the liquid water are relatively free to move, giving a more disordered state. This is shown in **Figure 4**. Entropy increases when ice melts and the change in entropy is positive.

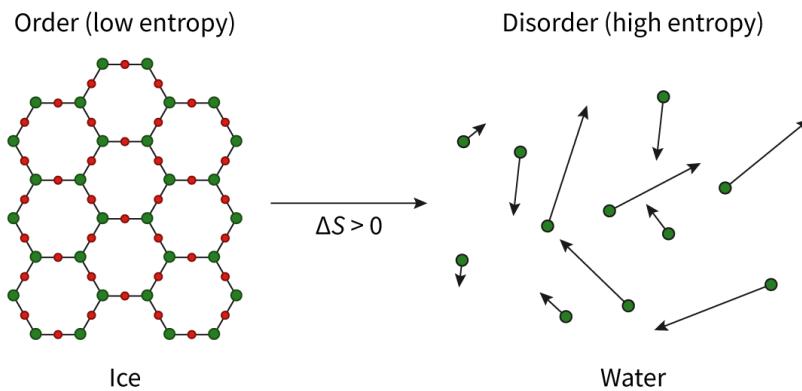


Figure 4. When ice melts, the entropy increases.

More information for figure 4

The image is a diagram illustrating the concept of increased entropy as ice melts into water. On the left side of the diagram, there are structured hexagonal formations representing the ordered crystal lattice of solid ice. Each intersection point of the lattice has green and red dots representing molecules. An arrow points from the ice structure to a depiction of liquid water on the right. In the liquid state, the molecules are dispersed and appear randomly arranged, indicating more freedom of movement and disorder. Arrows around these molecules show different directions in which they are moving, symbolizing the transition to a higher entropy state when ice becomes liquid.

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Worked example 2

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Determine the change in entropy when 55 J of energy is used to boil water at 100 °C.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$\Delta Q = 55 \text{ J}$ $T = 100 \text{ }^{\circ}\text{C}$ $= 100 + 273$ $= 373 \text{ K}$ Water boiling is a phase change and takes place at a constant temperature.
Step 2: Write out the equation.	$\Delta S = \frac{\Delta Q}{T}$
Step 3: Substitute the values given.	$= \frac{55}{373}$
Step 4: State the answer with appropriate units and the number of significant figures used.	$= 0.147 \text{ J K}^{-1} = 0.15 \text{ J K}^{-1} \text{ (2 s.f.)}$

Second law of thermodynamics

Imagine a glass of water at room temperature. Without any work being done on the water, the thermal energy is ‘magically’ transferred from the water to the room and freezes the water into ice, making the room warmer. This would obey the first law of thermodynamics, which is the application of conservation of energy, so why don’t we see this happening in real life?

Almost all processes in real isolated systems are **irreversible**. We would not expect a broken egg to become whole again. The more you shuffle playing cards, the more mixed up in sequence they become. The water from melting ice in a room at 20 °C will not become ice again no matter how long you wait.

In all these examples, the entropy increases. Therefore, entropy is telling us the **arrow of time** – the direction that a system, including our universe, can evolve in.

If a process involving an increase in entropy in an isolated system *were* reversible, we would see the entropy of the isolated system *decrease* when it was run backwards. This is not possible. For a process to be reversible, the entropy change has to be zero ($\Delta S = 0$). This way, when the process is run backwards, there is still no decrease in entropy.

It is possible to find examples of non-isolated systems, such as air conditioners and refrigerators, which can decrease the entropy locally (for example, making cold air colder and warm air warmer). However, this is compensated for by an equal or greater increase of the entropy of the



surroundings.

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An infinitely slow adiabatic compression or expansion of a gas is an example of a reversible thermodynamic process. Reversible processes are characterised by a change in entropy equal to zero. Reversible processes do not exist in reality; they are idealisations of real processes which help us understand the maximum efficiency a system could achieve in ideal working conditions.

In the 1850s, physicist Rudolf Clausius and engineer Lord Kelvin each made a different statement on the second law of thermodynamics.

Rudolf Clausius stated that: ‘Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time.’ In other words, thermal energy cannot spontaneously be transferred from a cold body to a hot body without some work being done (by, for example, a refrigerator).

Consider a real isolated system. When thermal energy Q transfers from a hot body at temperature T_h to a cold body at temperature T_c ($T_h > T_c$) (**Figure 5a**), the net change of entropy is:

$$\begin{aligned}\Delta S &= \frac{\Delta Q}{T} \\ &= \left(-\frac{Q_h}{T_h} + \frac{Q_c}{T_c} \right)\end{aligned}$$

For a transfer of energy between reservoirs within an isolated system, the energy lost by the hot reservoir is equal to the amount gained by the cold, thus we can say:

$$\Delta S = Q \left(-\frac{1}{T_h} + \frac{1}{T_c} \right)$$

where

$$\Delta S > 0$$

If we imagine thermal energy Q transferring from a cold body to a hot body (**Figure 5b**), the net change of entropy is:

$$\begin{aligned}\Delta S &= \left(-\frac{Q}{T_c} + \frac{Q}{T_h} \right) \\ &= Q \left(\frac{1}{T_h} - \frac{1}{T_c} \right) < 0\end{aligned}$$

Therefore this process does not happen without separate entropy increase occurring at the same time.

Note that despite energy moving between two temperatures, the use of $\Delta S = \frac{\Delta Q}{T}$ is still valid, as it is being used within each isolated system (hot and cold reservoirs). As each reservoir maintains a constant temperature, the equation is valid and may be used here.



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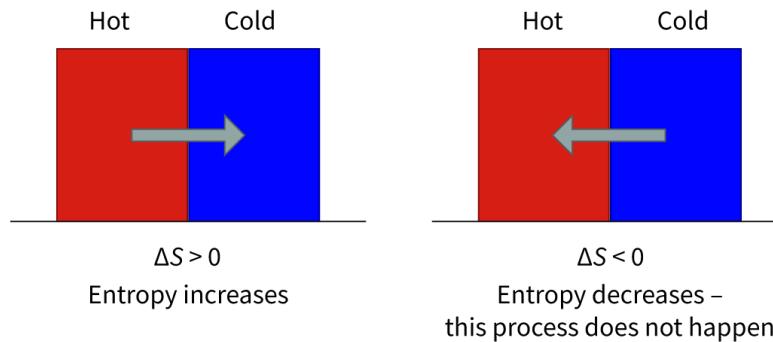


Figure 5. Thermal energy transfers between two bodies.

More information for figure 5

The image features a diagram illustrating thermal energy transfer between two bodies. On the left side, a red rectangle labeled 'Hot' is next to a blue rectangle labeled 'Cold'. An arrow points from the red rectangle to the blue one, indicating heat flow from hot to cold. On the right side, the same setup is shown, but the arrow points from the blue 'Cold' rectangle back to the red 'Hot' rectangle, implying work is needed for heat to flow in this direction.

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The important word in the statement is **spontaneously**. Work must be done in order to transfer thermal energy from a cold body to a hot body. For example, air conditioners and refrigerators transfer thermal energy from a cool space to the hotter surroundings but they do work and require power to do so.

🔗 Nature of Science

Aspect: Global impact of science

In the 19th century, scientists attempted to apply the second law of thermodynamics to a universal scale. They suggested that with sufficient time, the universe would approach a state where the thermal energy was evenly spread out throughout it. This is known as the heat death of the universe (the Big Chill or Big Freeze).

The video introduces the modern view about the origin of the universe.



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Video 2. Origins of the universe.

Think about the origin of the universe and its possible ultimate fate. Has the entropy in the universe been increasing?

Lord Kelvin stated that: 'It is impossible to construct a device that operates in a cycle and produces no other effect than the production of work and the transfer of heat from a single body.'

In other words, in a cyclic process ([section B.4.4 \(/study/app/math-aa-hl/sid-423-cid-762593/book/heat-engines-and-the-carnot-cycle-hl-id-44327/\)](#)), it is impossible to completely convert heat into work. This means that some of the thermal energy is wasted. A cyclic process converting heat into work can never be 100% efficient.

Theory of Knowledge

The second law of thermodynamics is not time-symmetric. Entropy in a real isolated system will always increase with time so the reverse process cannot take place. Hence, irreversibility is connected to the direction of time. Entropy gives us a way to distinguish 'past' and 'future'. In the future, the overall entropy of the universe will be greater than it was in the past. This link between time and the nature of thermodynamics is not fully understood.

Arthur Stanley Eddington was the first person to use the term 'Arrow of Time' in his book *The Nature of the Physical World* (1927), with the direction of time defined as the direction of a thermodynamic process in which entropy increases.

Physicists are still not 100% sure why time only appears to flow in one direction. Research what the conditions of a 'justified true belief' are, and evaluate why physicists are still not certain of the answer.

Work through the activity to check your understanding of the second law of thermodynamics.



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Activity

- **IB learner profile attribute:**
 - Knowledgeable
 - Thinker
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 15 minutes
- **Activity type:** Pair activity

Instructions

The Clausius and Kelvin expressions of the second law of thermodynamics are equivalent, although they are expressed differently.

Work as a pair and suggest examples, with diagrams, to illustrate the following statements:

- When the Clausius statement is not true, the Kelvin statement is not true either.
- When the Kelvin statement is not true, the Clausius statement is not true either.

Watch the video to see an explanation.

Second Law of Thermodynamics - Sixty Symbols



Second law of thermodynamics

5 section questions ^

Question 1

HL Difficulty:



Student view

In the equation $S = k_B \ln \Omega$, what does Ω represent?

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1 The number of microstates



2 The number of macrostates

3 The entropy of the system

4 The resistance of a circuit

Explanation

Ω represents the number of microstates in a system.

Question 2

HL Difficulty:

Three coins are flipped randomly. Which of the following is true?

1 There are 8 microstates and 4 macrostates.



2 There are 4 microstates and 8 macrostates.

3 There are 6 microstates and 2 macrostates.

4 There are 2 microstates and 6 macrostates.

Explanation

The possible outcomes are below:

Possible macrostates	Possible microstates	Number of microstates
3 heads, 0 tails	HHH	1
0 heads, 3 tails	TTT	1
2 heads, 1 tail	THH, HTH, HHT	3
1 head, 2 tails	HTT, THT, TTH	3

We can see that there are four possible macrostates, and altogether, 8 possible microstates.

Question 3

HL Difficulty:

Determine the change in entropy of a 2.0 kg block of ice when it melts slowly at 0.0 °C. Give your answer to an appropriate number of significant figures.



Student view

Specific latent heat of fusion of ice is 330 kJ kg⁻¹.

The change in entropy is 1 J K^{-1} .✓ kJ K^{-1} .Overview
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Accepted answers and explanation

#1 2.4

General explanation

$$\begin{aligned} T &= 0.0^\circ\text{C} \\ &= 0.0 + 273 \\ &= 273 \text{ K} \end{aligned}$$

The latent heat absorbed by the ice in order for it to melt is:

$$\begin{aligned} \Delta Q &= mL = 2 \times 330 \\ &= 660 \text{ kJ} \\ &= +660\,000 \text{ J} \end{aligned}$$

The change in entropy is:

$$\begin{aligned} \Delta S &= \frac{\Delta Q}{T} \\ &= +\frac{660\,000}{273} \\ &= +2400 \text{ J K}^{-1} \\ &= 2.4 \text{ kJ K}^{-1} \text{ (2 s.f.)} \end{aligned}$$

Question 4

HL Difficulty:

A gas at temperature T_1 can undergo either an isovolumetric process or an isobaric process. In both cases, the new temperature, T_2 , is the same. Determine which of the following statements is true.

- 1 The isobaric process gives rise to a larger change in entropy than the isovolumetric process. ✓
- 2 The isovolumetric process gives rise to a larger change in entropy than the isobaric process.
- 3 There is no entropy change for the two processes.
- 4 The entropy change for the two processes is the same.

Explanation

For both processes, the temperature change of the gas is the same. Hence, the change in internal energy, ΔU , is the same.

For the isovolumetric process there is no work done as $W = P\Delta V = 0$. However, the volume will change for the isobaric process and work will be done: $W \neq 0$

Hence, from the first law of thermodynamics, $Q = \Delta U + W$, the thermal energy transferred during the isobaric process must be greater than that transferred during the isovolumetric process. This means that the entropy change will be larger for the isobaric process.



Student view

Question 5

HL Difficulty:



A system has 8.2×10^3 microstates. What is the entropy of the system?

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1 $S = 1.2 \times 10^{-22} \text{ J K}^{-1}$



2 $S = 1.1 \times 10^{-19} \text{ J K}^{-1}$

3 $S = 2.9 \times 10^{-23} \text{ J K}^{-1}$

4 Cannot be calculated from the data.

Explanation

Use the equation: $S = k_B \ln \Omega$

$$S = 1.38 \times 10^{-23} \times \ln(8200)$$

$$S = 1.244 \times 10^{-22} \text{ J K}^{-1}$$

$$S = 1.2 \times 10^{-22} \text{ J K}^{-1} \text{ (to 2 s.f.)}$$

Give your answer to the correct number of significant figures and with correct units.

B. The particulate nature of matter / B.4 Thermodynamics (HL)

Heat engines and the Carnot cycle (HL)

B.4.11: Heat engines (HL) B.4.12: Efficiency of heat engines (HL) B.4.13: Carnot cycle and the efficiency limit of a heat engine (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Understand that cyclic gas processes are used in heat engines.
- Understand that different cycles can be used in heat engines and calculate the efficiency of heat engines.
- Understand that the Carnot cycle limits the efficiency of a heat engine.

In the late nineteenth and early twentieth centuries, there was a second industrial revolution.

Large machines and factories were built and new ways of transporting raw materials and finished goods were invented (**Figure 1**).

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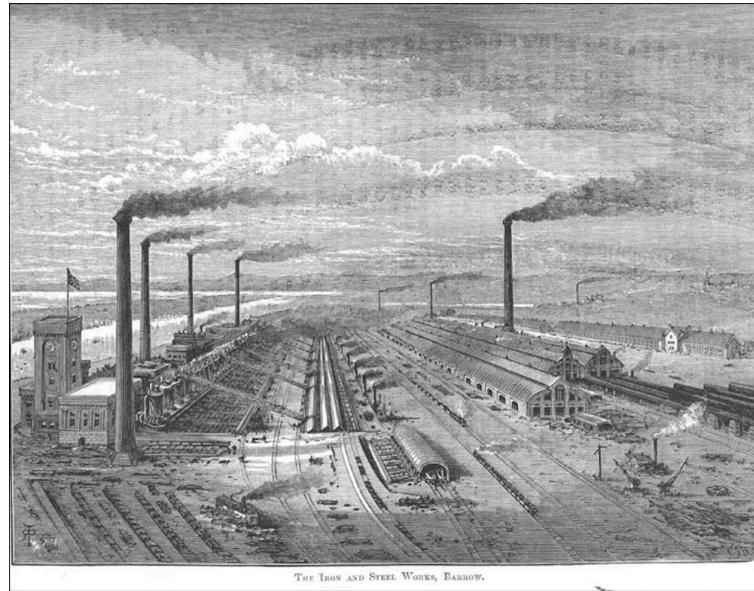


Figure 1. A steelworks in England in 1873.

Source: "Barrow Steelworks (https://en.wikipedia.org/wiki/File:Barrow_Steelworks.jpg)" by unknown is in the public domain

So what drove this second industrial revolution? How did goods go from being transported by horse and cart to being transported by steam train?

Heat engines

The second industrial revolution came about because of the heat engine. This is a system that converts thermal energy into work.

The four thermodynamic processes are ([section B.4.2 \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-first-law-of-thermodynamics-hl-id-44323/\)](#)): isothermal, isobaric, isovolumetric and adiabatic. **Interactive 1** shows the *PV* diagram of a thermodynamic cycle that cycles from A to D and so on. Identify the thermodynamic process by dragging the correct label to each stage of the cycle.



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Interactive 1. Identify the correct stages in a thermodynamic cycle.

More information for interactive 1

This is a drag and drop activity that helps users understand thermodynamic processes by labeling different segments of a pressure-volume (P-V) diagram. Pressure is on the vertical axis while the volume is on the horizontal axis.

The diagram features a closed loop with four points labeled A, B, C, and D, connected in sequence with arrows showing the direction of the cycle. Each segment between the points represents a different thermodynamic process. Users have to drag and drop labels into the blank boxes that correspond to each segment, identifying whether the process is isobaric, isothermal, or isovolumetric.

The available labels in the image are: isobaric constant pressure, isothermal constant temperature, and isovolumetric constant volume. There is a curve between points A and B, where the temperature remains constant as volume increases and pressure decreases. This segment represents an isothermal (constant temperature) expansion. The segment from point B to C is a vertical line, which means the volume does not change while the pressure decreases. So, this segment represents an isovolumetric (constant volume) process. The horizontal segment from point C to D shows that the pressure is constant while the volume decreases. So, this segment represents an isobaric (constant pressure) process. Finally, the vertical segment from D to A shows pressure increasing at constant volume. So, this segment represents an isovolumetric (constant volume) process.

By dragging labels like isobaric constant pressure, isothermal constant temperature, and isovolumetric constant volume to the appropriate parts of the diagram, users reinforce their understanding of how pressure and volume interact in these systems. Once all the labels are placed correctly, the user can press the Check button to confirm their answers.

Solution:

Segment A to B, Label: isothermal constant temperature.

Segment B to C, Label: isovolumetric constant volume.

Segment C to D, Label: isobaric constant pressure.



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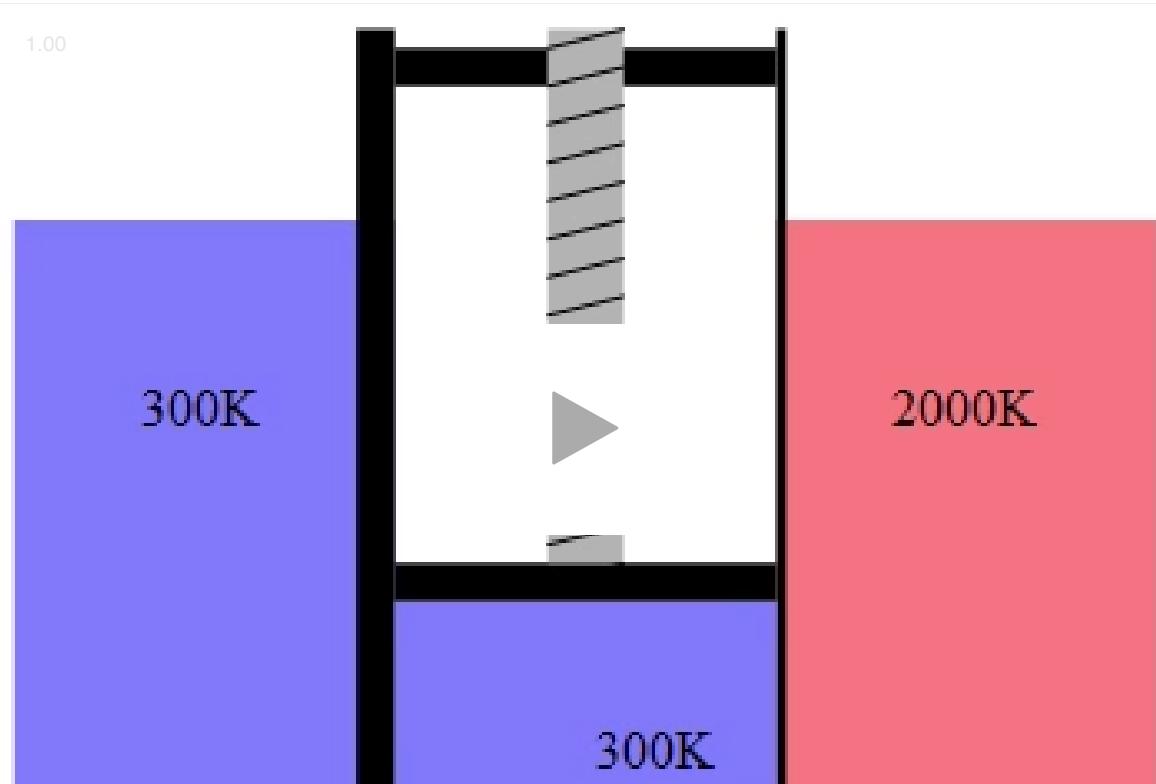
Segment D to A, Label: isovolumetric constant volume.

This activity reinforces students' understanding of the relationship between pressure and volume in thermodynamic systems, while helping them visually distinguish between different types of processes.

Heat engines use these cyclic gas processes to produce work. They can use different thermodynamic cycles, with different combinations of processes.

Stirling heat engine

Let's look at a simple heat engine first – a Stirling engine (**Interactive 2**). The Stirling engine works by compressing and expanding a gas in a continuous cycle. An external heat source provides heat to a gas contained in a chamber whose top part is a piston. The temperature of the gas increases until it is equal to that of the heat source. Since the volume of the gas is constant, the pressure increases. As a result, the gas expands at constant temperature, moving the piston up. The gas then loses heat to the heat sink (i.e. the cooler part of the engine) at constant volume, and then compresses at constant temperature, so that the piston is back in its initial position and the gas returns to its original volume. The cycle then repeats itself.



Interactive 2. A Stirling Engine.

More information for interactive 2

An animation video of the operation of a Stirling heat engine, illustrating the repetitive back-and-forth linear motion of a piston within a chamber containing gas. The chamber containing gas is in the middle and it has a piston at the top. The chamber is in thermal contact with two reservoirs at different temperatures: a cold reservoir at 300K on the left and a hot reservoir at 2000K on the right.

Initially, the gas inside the chamber is at 300K. As heat flows from the hot reservoir, the temperature of the gas inside the chamber increases to 2000K and the gas expands, causing the piston to move upward. This represents the expansion phase of the Stirling cycle. The gas then comes into contact with the cold reservoir, and the temperature of the gas inside

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the chamber decreases again to 300K losing heat. As a result, the gas compresses, causing the piston to move downward. The process continues repeatedly, demonstrating how thermal energy is converted into mechanical work through the motion of the piston.

Look at **Video 1** to see a working model of a Stirling engine.

Stirling Engine kit, low temperature



Video 1. A Stirling engine.

More information for video 1

The video presents a working model of a Stirling engine, demonstrating how temperature differences can be harnessed to produce mechanical motion. It begins with a clear view of the small engine positioned atop a vibrant yellow and green teacup and saucer. The engine's structure is simple yet effective, featuring a brass flywheel and silver metallic components. As the video opens, the words "Stirling" and "Engine" are overlaid, framing the focus of the demonstration.

Hot water is poured into the teacup from a white electric kettle, and the Stirling engine is carefully placed on top. Almost immediately, the flywheel begins to rotate in a counter-clockwise direction. This movement is highlighted with the on-screen text "Rotating here anticlockwise." This visual cue draws attention to the core principle being demonstrated: when the base of the engine is heated, the expansion and contraction of the gas inside the engine produce a cyclic motion that powers the flywheel.

The scene then transitions to a close-up side view, focusing on the flywheel's smooth, continuous rotation. The action is slowed to 4x slow motion, allowing a detailed observation of the mechanical components as they interact—revealing the internal movements that drive the engine's functionality. The coordinated motion of pistons and connecting rods becomes more evident, illustrating how thermal energy is converted into mechanical work.

Next, the engine is shown atop a teacup now filled with what appears to be hot coffee. The text "A pot of hot coffee is also applicable" confirms that any sufficiently hot liquid can serve as a heat source. Again, the engine operates successfully, with the flywheel maintaining its steady counter-clockwise rotation. This emphasizes that the heat source need not be limited to boiling water; any substance with enough thermal energy to establish a temperature gradient across the engine can sustain its operation.

The demonstration then shifts to the opposite end of the temperature spectrum. The hot water is poured out, and the Stirling engine is placed on a clear plastic bowl filled with ice. The text "Ice -18°C" appears on screen, indicating the extremely cold conditions now in use. Remarkably, the engine begins to rotate again—this time in the opposite direction, clockwise. The accompanying on-screen text "turns here clockwise" underscores the reversal of motion due to the inverted temperature gradient: now, the base of the engine is cold relative to the surrounding air, and the engine continues to function by drawing heat from the warmer top.

Another slow-motion sequence follows with the text appearing "4x Slow motion" offering a detailed view of the engine's clockwise operation. The mechanical components are seen moving rhythmically, propelled by the thermal energy transferred from the environment to the cold base. The engine is briefly lifted from the ice, causing the motion to cease, then returned—prompting the flywheel to resume spinning. This highlights the engine's direct dependence on a continuous

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temperature differential for operation.

The key learning outcome centers around the fundamental operation of a Stirling engine, which converts thermal energy into mechanical energy through cyclic compression and expansion of gas in a closed system. The presence of a temperature gradient—whether created by a hot liquid or ice—is essential for the engine's motion. The direction of rotation depends on the orientation of that gradient. The demonstration reinforces the concept of energy transfer and the practical application of heat engines, offering a visually compelling and mechanically rich example of thermodynamic principles in action.

Work through the slides in **Interactive 3** to see the PV diagrams for a Stirling engine.

Interactive 3. PV Diagrams to Show How a Stirling Engine Works.

More information for interactive 3

This interactive is designed to walk users through the PV diagrams of a Stirling engine and help understand its thermodynamic cycle. A slideshow viewer with five images, each accompanied by a descriptive text panel on the right side. The slideshow navigation bar is located at the bottom, displaying the current slide number (1 / 5 or 2 / 5) and providing buttons to move between slides. A blue progress indicator shows the position within the slideshow. In the bottom right corner, there is an expand button to view the images in full screen.

The first slide shows a PV diagram for the Stirling engine. The graph plots Pressure (P) on the vertical axis and Volume (V) on the horizontal axis. The curve shows the process of gas expanding as it absorbs heat Q_{h1} from a hot reservoir at temperature T_h . The initial point is labeled A and the gas starts with a cold temperature T_c before absorbing heat and moving to point B. The text at right hand side reads — “Consider a gas with a cold temperature T_c in a piston. The thermodynamic cycle starts with an isovolumetric process from A to B. The gas absorbs heat Q_{h1} from a hot reservoir with temperature T_h .”

The second slide continues the isothermal expansion process. The image now highlights the work done by the gas W_1 as it expands from point B to C at constant temperature T_h . The area under the curve represents the work done by the gas during this expansion, and heat Q_{h2} is transferred to the gas. The text at right hand side reads — “Due to the high pressure attained, the gas undergoes isothermal expansion with constant temperature T_h and pushes the piston, providing useful work done. Heat Q_{h2} is transferred to the gas. As the process is isothermal, the change in internal energy ΔU is zero, so $Q = W$ (heat gained = work done). The area under the curve BC is the work done. For expansion, this is the work done W_1 by the gas: $W_1 > 0$ ”

The third slide shows the cooling process. Here, the gas is transferred from point C to point D while in contact with a cold reservoir at temperature T_c . The volume stays constant as the gas loses heat Q_{c3} , and since there's no change in volume, the work done is zero. The text at right hand side reads — “The hot gas of the piston is then in contact with the cold reservoir of T_c . This is a process of isovolumetric cooling from C to D by transferring heat Q_{c3} to the reservoir. Since there is no change in volume, the work done is zero.”



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The fourth slide presents the isothermal compression from point D back to point A. During this phase, heat Q_{C4} is transferred from the gas to the cold reservoir. The area under the curve CA represents the work done on the gas, and it is negative, as the gas is compressed. The text at right hand side reads — “The last process of this cycle is an isothermal compression from D back to A. Heat Q_{C3} is transferred from the gas to the cold reservoir. The area under the curve CA is the negative work done ($-W_2$) on the gas. It is negative according to the convention in section B.4.2.”

The fifth slide concludes the cycle with a net work calculation. It shows the total work done by the gas, represented as $W_{\text{net}} = W_1 - W_2$, the area enclosed by the loop in the PV diagram. This represents the total energy produced by the Stirling engine during the cycle. The text at right hand side reads — “The net work done by the gas is $W_{\text{net}} = W_1 + (-W_2) = W_1 - W_2$. It can be shown graphically that the net work done is equal to the area enclosed by the loop of the thermodynamic cycle on the PV diagram.

In summary, the thermodynamic cycle of a Stirling engine is:

1. Extract heat from a hot reservoir (for example, the heat produced by burning natural gas).
2. Use some of the extracted heat to provide useful work done (for example, pushing a piston).
3. Get rid of the unused heat into a cold reservoir (for example, the surroundings).
4. Repeat the cycle.

International Mindedness

Heat engines produce work and also produce waste heat. The input energy sources are often coal, natural gas and oil, which produce greenhouse gases like CO₂, which is a cause of global warming (see subtopic [B.3 \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44289\)\)](#).

Figure 2 shows the annual changes in global fossil CO₂ emissions. You can see how the biggest drop in global CO₂ emissions was recorded during the Covid-19 pandemic lockdowns. Since then, however, the level of CO₂ has risen again.

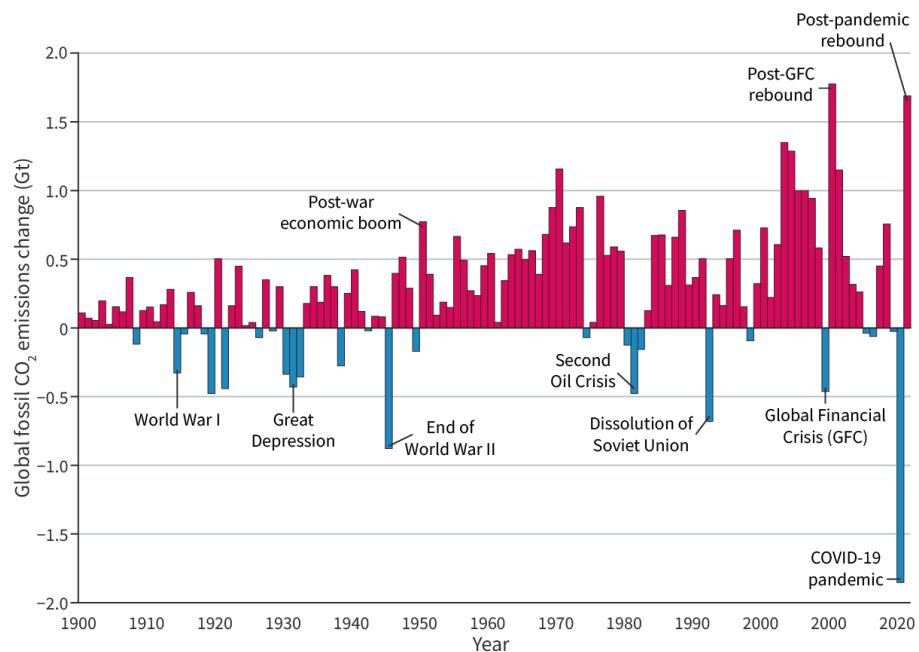


Figure 2. Annual changes in global fossil CO₂ emissions (1900—2020).

[More information for figure 2](#)



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The bar chart represents annual changes in global fossil CO₂ emissions from 1900 to 2020. The X-axis represents years, ranging from 1900 to 2020, while the Y-axis shows changes in CO₂ emissions in gigatonnes (Gt), ranging from -2.0 to 2.0. The chart highlights several significant historical events and their impact on CO₂ emissions.

Key events include: - World War I around 1914 - The Great Depression in the 1930s - End of World War II in the mid-1940s - The Post-War Economic Boom around 1950 - The Second Oil Crisis in the 1970s - The Dissolution of the Soviet Union around 1990 - Global Financial Crisis (GFC) in 2008 - COVID-19 pandemic in 2020

A marked decline in emissions is visible during the World Wars, the Great Depression, and most notably during the COVID-19 pandemic, followed by a post-pandemic rebound. Emissions surged during the post-war economic boom and again post-GFC.

[Generated by AI]

Table 1 ranks the largest emitters of CO₂ in 2020.

Table 1. The 12 largest emitters of CO₂ (2020).

Rank	Country	CO ₂ emissions (millions of metric tons)
1	China	10 668
2	United States	4713
3	India	2442
4	Russia	1577
5	Japan	1031
6	Iran	745
7	Germany	644
8	Saudi Arabia	626
9	South Korea	598
10	Indonesia	590
11	Canada	536
12	Brazil	467



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Are there substitutes for heat engines? How can we improve the efficiency of heat engines as much as possible? How effective is replacing fuel engines in vehicles with electric motors in terms of CO₂ emission reduction?



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The Carnot cycle

The Carnot cycle was proposed by Sadi Carnot in 1824. This cycle consists of four reversible processes, meaning that the cycle as a whole is also reversible. Watch the video in **Interactive 4** to see the cycle.

Carnot Cycle 1



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Interactive 4. The Carnot Cycle.

 More information for interactive 4

This interactive video consists of an embedded YouTube video that explains the Carnot cycle, a fundamental thermodynamic cycle used to model the most efficient heat engine. The interactive features a user-friendly video player interface. On the bottom left, a play/pause button allows users to control playback, while a draggable progress bar displays the current position with tick markers indicating key points in the video. On the right side, a timestamp shows the elapsed and total duration, and a fullscreen button enables users to expand the video for a better viewing experience.

The Carnot cycle, as presented in the video, consists of four distinct thermodynamic stages illustrated clearly on a Pressure-Volume (PV) diagram. The x-axis represents volume (V), and the y-axis represents pressure (P). The path of the cycle forms a closed loop through four key states, A, B, C, and D, with labels marking "Hot Isotherm", "Cool Isotherm", and the Adiabat in between.

The first stage is Isothermal Expansion, from A to B. The gas is in contact with a hot reservoir at a constant temperature T_h . It absorbs heat Q_h from the reservoir and expands isothermally, that is, while maintaining constant temperature. As it expands, the gas does work on the piston, increasing its volume without changing its internal energy. A textbox appears in the top right of the video reading: "*From A to B, the gas is absorbing heat from the hot reservoir and expanding with constant temperature (isothermal expansion).*"

The second stage is Adiabatic Expansion, from B to C. The hot reservoir is removed, and the gas continues to expand without any heat exchange. As it expands adiabatically, its internal energy decreases, leading to a drop in temperature and pressure. This causes the gas to move to a lower isothermal curve, labeled "Cool Isotherm". A textbox appears that reads: "*From B to C, the hot reservoir is removed. The gas continues to expand but it is cooling down due to adiabatic expansion, reaching a lower isothermal line.*"

The third stage is Isothermal Compression, from C to D. The gas is now in contact with a cold reservoir at a constant temperature T_c . It undergoes compression, reducing its volume while maintaining a constant temperature. During this process, the gas releases heat Q_c to the cold reservoir. As the volume decreases, the pressure increases. The corresponding textbox states: "*From C to D, the gas is in contact with the cold reservoir. However the temperature is constant because the gas is compressed to a smaller volume with higher pressure (gas law: $PV = nRT$).*"



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The final stage is Adiabatic Compression, from D to A. The cold reservoir is removed, and the gas is compressed adiabatically, meaning no heat is exchanged. As compression continues, the temperature and pressure of the gas increase. This process brings the system back to its original state on the hot isothermal line, completing the cycle. The textbox during this portion reads: "From D to A, the cold reservoir is removed. The gas continues to shrink but its temperature increases due to adiabatic compression, returning to the higher isothermal line and initial state."

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The reason is that, for adiabatic processes, there is no heat transfer, therefore the heat transferred to the cold reservoir (waste heat) is reduced.

Efficiency of heat engines

The energy transfers of a Stirling engine are shown in the Sankey diagram in **Figure 3**.

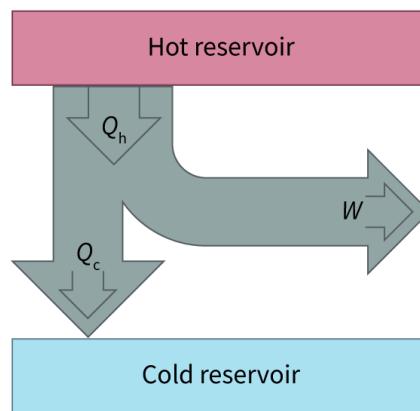


Figure 3. Sankey diagram for a Stirling engine.

More information for figure 3

The Sankey diagram illustrates the energy transfer process in a Stirling engine. The diagram is comprised of three main components: the hot reservoir, an arrow labeled 'Q_h' pointing downwards, the cold reservoir, and an arrow labeled 'Q_c' also pointing downwards. A third arrow, labeled 'W', extends horizontally to the right. The hot reservoir is placed at the top and is represented by a pink rectangle, while the cold reservoir is represented by a blue rectangle at the bottom. The arrows depict the direction of heat and work transfer: 'Q_h' represents the heat input from the hot reservoir, 'Q_c' represents the heat rejected to the cold reservoir, and 'W' indicates the work done by the engine. The diagram helps in understanding the flow of heat and work within the energy system of the Stirling engine.

[Generated by AI]

The energy transfers can also be described by the equation in **Table 2**.

Table 2. Equation for heat extracted from the hot reservoir.

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Equation	Symbols	Units
$Q_h = W + Q_c$	Q_h = heat extracted from the hot reservoir	joules (J)
	W = work done in the thermodynamic cycle	joules (J)
	Q_c = heat released to the cold reservoir	joules (J)

The efficiency of a thermodynamic cycle, η , is given by the equation:

$$\eta = \frac{\text{useful work } (W)}{\text{input energy } (Q_h)}$$

The input energy is the heat drawn from the hot reservoir, and useful work is the energy remaining after exhausting ‘waste’ heat to the cold reservoir.

The efficiency of the Carnot cycle is given by the equation in **Table 3**.

Table 3. Equation for efficiency of the Carnot cycle.

Equation	Symbols	Units
$\eta_{\text{Carnot}} = 1 - \frac{T_c}{T_h}$	η_{Carnot} = efficiency of the Carnot cycle	Unitless
	T_c = temperature of the cold reservoir	kelvin (K)
	T_h = temperature of the hot reservoir	kelvin (K)

DP physics does not require you to derive the equation for the efficiency of a Carnot cycle, but it is useful to know the derivation.

The Carnot cycle returns the system to its initial temperature, so there is no overall change in internal energy. The total work done by the gas in a single cycle is the net heat absorbed:

$$W_{\text{net}} = Q_{AB} - Q_{CD}$$

The total change in entropy in one cycle is:

$$\Delta S_{\text{cycle}} = \Delta S_{AB} + \Delta S_{BC} + \Delta S_{CD} + \Delta S_{DA}$$

Change in entropy is $\Delta S = \frac{\Delta Q}{T}$ and the adiabatic processes ($B \rightarrow C$) and ($D \rightarrow A$) have no heat transfer, so the total change in entropy in the Carnot cycle is:

$$\begin{aligned}\Delta S_{\text{Carnot}} &= \Delta S_{AB} + \Delta S_{CD} \\ &= \frac{Q_{AB}}{T_h} - \frac{Q_{CD}}{T_c}\end{aligned}$$

The Carnot cycle is reversible in nature, so:

$$\begin{aligned}\Delta S_{\text{Carnot}} &= \frac{Q_{AB}}{T_h} - \frac{Q_{CD}}{T_c} \\ &= 0\end{aligned}$$

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$$\frac{Q_{AB}}{T_h} = \frac{Q_{CD}}{T_c}$$

As:

$$\eta = \frac{\text{useful work}}{\text{input energy}}$$

then:

$$\begin{aligned}\eta &= \frac{(Q_{AB} - Q_{CD})}{Q_{AB}} \\ &= 1 - \left(\frac{Q_{CD}}{Q_{AB}} \right)\end{aligned}$$

For the Carnot cycle, $\frac{Q_{AB}}{Q_{CD}} = \frac{T_h}{T_c}$, so the efficiency is:

$$\eta_{\text{Carnot}} = 1 - \left(\frac{T_c}{T_h} \right)$$

From the Carnot cycle efficiency equation, we can deduce it is impossible for the cycle to achieve 100% efficiency as this would require:

- the hot reservoir has an infinitely high temperature, or
- the cold reservoir has a temperature of zero kelvin.

As the expansion and contraction of the gas is an isothermal process, the gas in the Carnot cycle must maintain the same temperature as the reservoirs. These stages must therefore happen very slowly, to allow the heat absorbed to do work, without increasing the internal energy of the gas. Therefore, the Carnot cycle is only hypothetical. If we want our engine to operate more quickly, or use realistic temperatures, we must sacrifice efficiency.

Worked example 1

Determine the efficiency of a Carnot cycle operating between reservoirs at 45 °C and 345 °C.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$T_h = 345 \text{ } ^\circ\text{C}$ $= 345 + 273$ $= 618 \text{ K}$
Step 2: Write out the equation.	$T_c = 45 \text{ } ^\circ\text{C}$ $= 45 + 273$ $= 318 \text{ K}$
Step 3: Substitute the values given.	$\eta_{\text{Carnot}} = 1 - \frac{T_c}{T_h}$ $= 1 - \frac{318}{618}$

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Solution steps	Calculations
Step 4: State the answer with appropriate units and the number of significant figures used.	$= 0.485$ $= 0.49$ (2 s.f.)

Worked example 2

The PV diagram in **Figure 4** shows a thermodynamic cycle from 1 to 4.

1. Calculate the work done on the piston in process A.
2. Calculate the work done by the piston in process C.
3. Calculate the net work done by the piston in the cycle.
4. The heat ejected to the cold reservoir is 8.5×10^5 J. Calculate the heat absorbed from the hot reservoir.
5. Calculate the efficiency of the cycle.

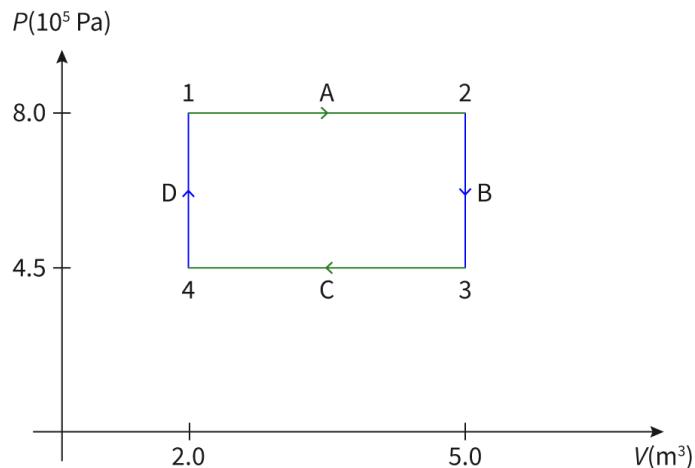


Figure 4. PV diagram of a thermodynamic cycle.

More information for figure 4

The image is a PV diagram illustrating a thermodynamic cycle represented by a rectangle. The X-axis, labeled as $V(\text{m}^3)$, ranges from 0 to 5.0, indicating volume in cubic meters. The Y-axis, labeled as $P(10^5 \text{ Pa})$, ranges from 4.5 to 8.0, indicating pressure in Pascals multiplied by 10^5 . The cycle progresses in a clockwise direction with labeled paths: A (from point 1 to 2), B (from point 2 to 3), C (from point 3 to 4), and D (from point 4 to 1). Each segment of the cycle is indicated by straight lines with arrows showing the direction of the process.

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1. Work done is the area under the line of process A:

$$\begin{aligned} W_A &= (5.0 - 2.0) \times (8.0 \times 10^5) \\ &= 2.4 \times 10^6 \text{ J} \text{ (2 s.f.)} \end{aligned}$$

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2. Work done is the area under the line of process C:

$$\begin{aligned} W_C &= (2.0 - 5.0) \times (4.5 \times 10^5) \\ &= -13.5 \times 10^5 \text{ J} \\ &= -1.4 \times 10^6 \text{ J (2 s.f.)} \end{aligned}$$

3. Net work done is the area enclosed by the rectangle ABCD:

$$\begin{aligned} W_{ABCD} &= (5.0 - 2.0) \times (8.0 \times 10^5 - 4.5 \times 10^5) \\ &= 10.5 \times 10^5 \\ &= 1.1 \times 10^6 \text{ J (2 s.f.)} \end{aligned}$$

4. $W = 1.1 \times 10^6 \text{ J}$
 $Q_c = 8.5 \times 10^5 \text{ J}$

$$\begin{aligned} Q_h &= W + Q_c \\ &= 1.1 \times 10^6 + 8.5 \times 10^5 \\ &= 1.96 \times 10^6 \text{ J} \\ &= 2.0 \times 10^6 \text{ J (2 s.f.)} \end{aligned}$$

5. $\eta = \frac{\text{useful work}}{\text{input energy}}$

$$\begin{aligned} \eta &= \frac{W}{Q_h} \\ &= \frac{1.1 \times 10^6}{2.0 \times 10^6} \\ &= 0.55 \text{ (or 55\%)} \text{ (2 s.f.)} \end{aligned}$$

Try the following activity to check your understanding of thermodynamic cycles.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Reflecting at all stages of the assessment and learning cycle
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Download the worksheet and complete the practice questions. The questions may cover concepts from previous sections. Remember to show all your working. You can check your answers on the last page.

[Worksheet](https://d3vrb2m3yrmfyi.cloudfront.net/media/edusys_2/content_uploads/Ph_B.4.4 ACTIVITY Thermodynamics.90cbcbe76962fc99bd3.pdf)





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4 section questions ^

Question 1

HL Difficulty:

Determine the efficiency of a Carnot cycle operating with a cold reservoir at 0.0 °C and a hot reservoir at 110 °C. Give your answer to an appropriate number of significant figures.

The efficiency is 1 0.29 ✓

Accepted answers and explanation

#1 0.29

29%

.29

General explanation

$$\begin{aligned}T_c &= 0.0 \text{ } ^\circ\text{C} \\&= 0.0 + 273 \\&= 273 \text{ K}\end{aligned}$$

$$\begin{aligned}T_h &= 110 \text{ } ^\circ\text{C} \\&= 110 + 273 \\&= 383 \text{ K}\end{aligned}$$

$$\begin{aligned}\eta_{\text{Carnot}} &= 1 - \frac{T_c}{T_h} \\&= 1 - \frac{273}{383} \\&= 0.29 \text{ (2 s.f.)}\end{aligned}$$

Question 2

HL Difficulty:

A manufacturer sells a heat engine which operates with a cold reservoir of 280 K and a hot reservoir of 400 K. The efficiency is quoted as 35%. Determine if this is a reasonable claim.

1 No ✓

2 Only if the heat engine operates using adiabatic and isothermal processes

3 Yes

4 Impossible to tell without further information

Explanation

The Carnot efficiency gives the maximum efficiency for heat engines operating with a given hot and cold reservoir. So in this case:

×

$$\begin{aligned}\eta &= 1 - \frac{T_c}{T_h} \\&= 1 - \frac{280}{400} \\&= 0.3 \text{ or } 30\%\end{aligned}$$



The quoted efficiency for this engine is greater than the theoretical maximum, and, hence, is not a reasonable estimate.

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Question 3

HL Difficulty:

A Carnot cycle has an efficiency of 42%. Calculate the hot reservoir temperature, T_h , if it operates with a cold reservoir temperature, T_c , of 310 °C. Give your answer to an appropriate number of significant figures.

The hot reservoir temperature is 730 °C

Accepted answers and explanation

#1 730

730 degrees C

730 °C

730 C

1010 K

General explanation

$$\begin{aligned}\eta_{\text{Carnot}} &= 42\% \\ &= 0.42\end{aligned}$$

$$\begin{aligned}T_c &= 310 \text{ °C} \\ &= 310 + 273 \\ &= 583 \text{ K}\end{aligned}$$

$$\eta_{\text{Carnot}} = 1 - \frac{T_c}{T_h}$$

$$\begin{aligned}T_h &= \frac{T_c}{(1 - \eta_{\text{Carnot}})} \\ &= \frac{583}{(1 - 0.42)} \\ &= 1005.2 \text{ K}\end{aligned}$$

$$\begin{aligned}1005.2 \text{ K} &= 1005.2 - 273 \\ &= 732.2 \text{ °C} \\ &= 730 \text{ °C (2 s.f.)}\end{aligned}$$

Question 4

HL Difficulty:

A heat engine operates with a hot reservoir at 90 °C and a cold reservoir at 25 °C. During a cycle, it absorbs 940 J of energy from the hot reservoir and returns 560 J to the cold reservoir. Calculate the change in entropy during one complete cycle. Give your answer to an appropriate number of significant figures.

The change in entropy is 0.71 J K⁻¹



Accepted answers and explanation

Student view

#1 0.71

General explanation

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$Q_{\text{in}} = -940 \text{ J}$

$Q_{\text{out}} = 560 \text{ J}$

Note that we have used a negative on the hot reservoir and positive on the cold reservoir as we are interested in total entropy change as a result of the engine - i.e. the hot reservoir loses 940 Joules and the cold reservoir gains 560 Joules.

$T_c = 25^\circ\text{C}$
 $= 25 + 273$
 $= 298 \text{ K}$

$T_h = 90^\circ\text{C}$
 $= 90 + 273$
 $= 363 \text{ K}$

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

$$\begin{aligned}\Delta S &= \frac{Q_{\text{in}}}{T_h} + \frac{Q_{\text{out}}}{T_c} \\ &= \frac{-940}{363} + \frac{560}{298} \\ &= -0.71 \text{ J K}^{-1} \text{ (2 s.f.)}\end{aligned}$$

B. The particulate nature of matter / B.4 Thermodynamics (HL)

Summary and key terms (HL)

Section

Student... (0/0)

Feedback



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Assign

Higher level (HL)

- The first law of thermodynamics as given by $Q = \Delta U + W$ results from the application of conservation of energy to a closed system.
- The work done by or on a system during a thermodynamic process is equal to the area under the corresponding curve on a PV diagram.
- The change in internal energy of an ideal gas is given by

$$\begin{aligned}\Delta U &= \frac{3}{2} N k_B \Delta T \\ &= \frac{3}{2} n R \Delta T\end{aligned}$$

- Entropy S is a thermodynamic quantity that relates to the degree of disorder of the particles in a system. It can be determined in terms of macroscopic quantities such as thermal energy and temperature as given by $\Delta S = \frac{\Delta Q}{T}$.
- Entropy S can also be expressed in terms of the properties of individual particles of the system as given by $S = k_B \ln \Omega$ where k_B is the Boltzmann constant and Ω is the number of possible microstates of the system.
- The second law of thermodynamics refers to the change in entropy of an isolated system and sets constraints on possible physical processes and on the overall evolution of the system.
- The entropy in a real isolated system almost always increases, while for a non-isolated system, the entropy can decrease locally, but the overall entropy of the system and surroundings still increases.



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- The four thermodynamic processes are isovolumetric, isobaric, isothermal and adiabatic processes, which are obtained by keeping one of the physical quantities fixed.
- An adiabatic process in monatomic ideal gases can be modelled by the equation $PV^{\frac{5}{3}} = \text{constant}$.
- The curve representing an adiabatic process is always steeper than the curve representing an isothermal process.
- Cyclic gas processes are used to run heat engines. The efficiency of a heat engine is given by $\eta = \frac{\text{useful work}}{\text{input energy}}$.
- The energy system in a cycle gas process can be described by $Q_h = W + Q_c$, i.e. heat absorbed from the hot reservoir is equal to the sum of useful work and the heat ejected to the cold reservoir.
- The Carnot cycle sets a limit for the efficiency of a heat engine at the temperatures of its heat reservoirs as given by $\eta_{\text{Carnot}} = 1 - \frac{T_c}{T_h}$.



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Key terms

Review these key terms. Do you know them all? Fill in as many as you can using the terms in this list.

1. A **closed** system is a system that can exchange **heat** with its surroundings, but not **matter**.
2. The first law of thermodynamics: thermal energy entering a closed system is equal to the sum of the change in **internal energy** of the system and **work done** by the system.
3. In an isothermal process, **temperature** remains constant. In an **isovolumetric** process, **pressure** remains constant. In a **constant pressure** process, **volume** remains constant.
4. **Entropy** is a measure of the amount of disorder of matter in a system.
5. The second law of thermodynamics: thermal energy cannot spontaneously transfer from a **hot** body to a **cold** body during a cyclic process.
6. The **efficiency** of a heat engine is determined by the ratio of **useful work done** to **input energy**.
7. The Carnot cycle limits the efficiency of a heat engine. It depends on the temperatures of its **hot reservoir** and its **cold reservoir**.

internal energy **hot** **efficiency** **hot reservoir** **matter**
efficiency **pressure** **temperature** **input energy** **part**
work done **Entropy** **closed**

Check

Interactive 1. Thermodynamics: Key Terms.

B. The particulate nature of matter / B.4 Thermodynamics (HL)

Checklist (HL)



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Higher level (HL)

What you should know

After studying this subtopic, you should be able to:

- Understand that the change in internal energy of a system is related to a change in temperature, and calculate change in internal energy.
- Understand that the work done by or on a closed system can be described in terms of pressure and change of volume.
- Understand and apply the first law of thermodynamics as given by $Q = \Delta U + W$.
- Understand isothermal, isovolumetric, isobaric and adiabatic processes.
- Use the equation $PV^{\frac{5}{3}} = \text{constant}$ to model an adiabatic process.
- Understand that entropy is a measure of the amount of disorder of particles in a system, and how it can be determined.
- Understand that the second law of thermodynamics relates to the change in entropy of an isolated system and solve problems involving entropy changes.
- Understand entropy in real isolated systems and non-isolated systems.
- Understand that cyclic gas processes are used in heat engines.
- Understand that different cycles can be used in heat engines and calculate the efficiency of heat engines.
- Understand that the Carnot cycle limits the efficiency of a heat engine.

B. The particulate nature of matter / B.4 Thermodynamics (HL)

Investigation (HL)

Higher level (HL)

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Research skills — Comparing, contrasting and validating information
- **Time required to complete activity:** 25 minutes
- **Activity type:** Group activity





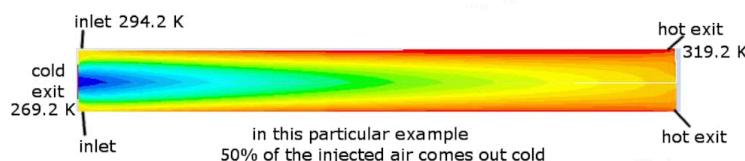
Your task

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The second law of thermodynamics predicts that the entropy of the universe will increase over time, and the universe will approach a state where its thermal energy is evenly spread out throughout it, which will lead to the heat death of the universe.

Is it possible to violate the second law of thermodynamics? Think about the following examples (you may need to carry out some research):

- A Vortex Tube, which can separate the inlet gas into a stream of hotter gas and another stream of colder gas (i.e. a more disordered to a less disordered).



A vortex tube.

Source: ["Fluent CFD simulation of vortex tube"](#)

(https://commons.wikimedia.org/wiki/File:Fluent_CFD_simulation_of_vortex_tube.jpg) by Jpolihronov is licensed under CC BY-SA 3.0 (<https://creativecommons.org/licenses/by-sa/3.0/deed.en>)

More information

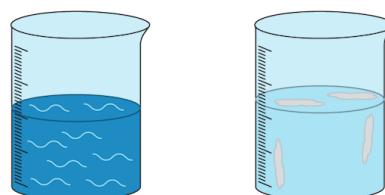
The diagram illustrates a vortex tube with three segments. On the left, there's an inlet labeled as 294.2 K, where air enters the tube. The tube is color-coded from blue on the left side, progressing through green and yellow, and turning red on the right side, indicating temperature changes.

On the left side, labeled as "cold exit," the temperature is marked at 269.2 K. This section of the tube is predominantly blue, suggesting cooling. The right side, labeled "hot exit," shows a temperature of 319.2 K and is colored red, indicating heating.

A central text in the diagram states, "in this particular example, 50% of the injected air comes out cold." This suggests a demonstration of the cooling and heating process within the vortex tube. The diagram is a straightforward representation of how air splits into hot and cold streams, demonstrating the functionality of the vortex tube.

[Generated by AI]

- When a plant grows, simple and scattered materials such as air, water and minerals combine to create a complex and highly organised structure.
- When water freezes at 0 °C, it goes from a less ordered structure to a more ordered structure (ice) with lower entropy.



Frozen water has a more ordered structure than water.

More information

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The image shows two beakers side by side. The left beaker contains water with wavy lines indicating a liquid state. The right beaker has ice present, indicated by solid shapes at the top and sides, suggesting a solid state. Both beakers have measurement markings on the side to give a sense of volume, but there is no specific labeling of units or numbers visible. This illustrates the different structural forms of frozen and liquid water.

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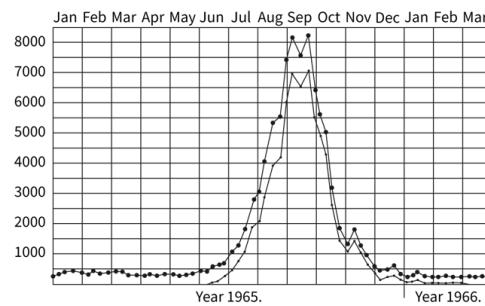
- Salt crystals can crystallise out of a concentrated salt water solution, forming an orderly array of sodium chloride.
- A water wave gradually disappears (i.e. zero amplitude) - from more disturbances to less disturbances?



Source: "Water drop impact on a water-surface"

(https://commons.wikimedia.org/wiki/File:Water_drop_impact_on_a_water-surface_-_%281%29.jpg)" by Davide Restivo is licensed under CC BY-SA 2.0 (<https://creativecommons.org/licenses/by-sa/2.0/deed.en>)

- The infection number of a contagious disease spontaneously decreasing.



A contagious disease can rapidly escalate and de-escalate.

More information

The graph is a line chart displaying data over a span of time, represented on the X-axis as time increments. The Y-axis represents an unspecified quantity. The chart shows a generally flat trend at the beginning and end, with a noticeable sharp peak in the middle, indicating a rapid escalation followed by a de-escalation of the represented data. Specific numerical values or labels for the data points are not provided in the image, but there is a clear peak, and the line graph is marked by dots at each data point, suggesting measured intervals. This pattern may illustrate an event or situation where the quantity rapidly increases and then decreases.

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Do any of these examples violate the second law of thermodynamics?

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Discuss the following questions:

- What if scientists really found a scenario that breaks the second law of thermodynamics?
- How might this affect our understanding of the universe and its fate?

B. The particulate nature of matter / B.4 Thermodynamics (HL)

Reflection (HL)

Section

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Feedback



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Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

HL Extension

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in [The big picture \(/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-hl-id-44324/\)](#).

- How can energy transfers and energy storage within a system be analysed?
- How can the future evolution of a system be determined?
- In what way is entropy fundamental to the evolution of the universe?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

Once you submit your response, you won't be able to edit it.

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Rate subtopic B.4 Thermodynamics (HL)

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