

# ENERGY, WORK AND HEAT

15-16 year-olds

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**Energy** is the ability to perform a work, and it's measured in **joules** ( $1\text{ J} = 1\text{ kg m}^2\text{ s}^{-2}$ ).

## Mechanical, kinetic and potential energy

### Kinetic energy KE

It's the energy of a body due to its **motion**. It depends on the mass  $m$  and the velocity  $v$ :

$$\text{KE} = \frac{1}{2}mv^2$$

### Potential energy PE

It's the energy contained on a body due to its **position** and/or **configuration**.

**Gravitational** potential energy of a mass  $m$  at a height  $h$  over the Earth's surface can be calculated as:

$$\text{PE}_g = mgh,$$

where  $h \ll R_E$  (being  $R_E$  the Earth's radius) and  $g$  is the value of gravity's acceleration.

### Mechanical Energy $E_m$

It's the **addition** of the **kinetic energy**, KE, plus the **potential energy**, PE:

$$E_m = \text{KE} + \text{PE}$$

## Conservation of energy

### Conservation mechanical energy

*When only **conservative forces** are acting on a body, its mechanical energy remains constant.*

Examples of **conservative forces** are: gravitational, elastic or electrostatic forces.

**Friction** is an example of a **non-conservative** or **dissipating** force.

### Conservation of energy

*In any nature's process, the **total** energy remains constant.*

## Energy transfer

Energy can be transferred/exchanged due to **work** or **heat**.

### Work $W$

**Work** is transferred when one body exert over another body **forces** that produce displacements or changes in their dimensions.

The work  $W$  done by a constant force  $\vec{F}$  can be calculated as:

$$W = \vec{F} \cdot \vec{d} = F \cdot d \cdot \cos \alpha,$$

where  $F$  is the value of the applied force,  $d$  is the displacement and  $\cos \alpha$  is the cosine of the angle formed by the force and the displacement.

### Heat $Q$

**Heat** is transferred between two bodies at a **different temperature**. The heat released by a body at a higher temperature is equal to the heat absorbed by the body at a lower temperature:  $Q_{\text{released}} + Q_{\text{absorbed}} = 0$ .

For historical reasons, heat is often measured in **calories** ( $1\text{ cal} = 4.18\text{ J}$ ).

## Work and Power

**Power**  $P$  is defined as the work  $W$  done by unit of time  $t$ :

$$P = \frac{W}{t} = \frac{\vec{F} \cdot \vec{d}}{t} = \vec{F} \cdot \vec{v}$$

In the **SI** power is measured in **watts** ( $1\text{ W} = 1\text{ J/s}$ ), being the **horsepower** ( $1\text{ CV} \approx 735\text{ W}$ ) another typical unit.

The **kilowatt hour**, kW h, is a unit of **energy** widely used in electrical bills:

$$1\text{ kW h} \cdot \frac{1000\text{ W}}{1\text{ kW}} \cdot \frac{3600\text{ s}}{1\text{ h}} = 3.6 \times 10^6\text{ W s} = 3.6 \times 10^6\text{ J}$$

## Heat effects on bodies

### Change of temperature

The relationship between the heat  $Q$  provided to a mass  $m$  of a substance and the change in temperature  $\Delta T$  of that mass is given by the equation:

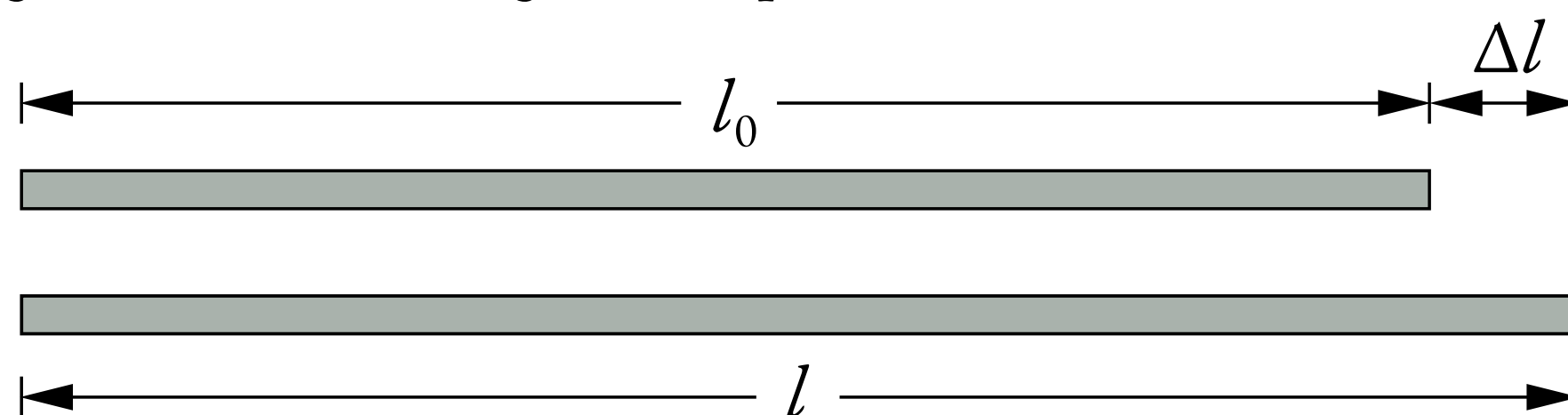
$$Q = m \cdot c \cdot \Delta T,$$

where  $c$  is the **specific heat** of that substance, which represents the amount of energy that should be provided to the unit of mass of that substance to increase its temperature one unit. In the **SI** it is measured in  $\text{J kg}^{-1}\text{ K}^{-1}$ .

### Expansion

Usually, a body increases its volume (*it expands*) when its temperature increases.

If we take a bar with an initial length  $l_0$  at an initial temperature  $T_0$  and we raise its temperature until  $T$ , the bar will increase its length until  $l$ . This length increase,  $\Delta l = l - l_0$ , is proportional to the initial length  $l_0$  and the change in temperature  $\Delta T = T - T_0$ :

$$\Delta l = \alpha \cdot l_0 \cdot \Delta T,$$


where  $\alpha$  is the **linear expansion coefficient**, whose units in the **SI** are  $\text{K}^{-1}$ . It can be demonstrated that the area expansion coefficient and the volumetric expansion coefficient are the double and the triple of the linear one:

$$\Delta S = 2\alpha \cdot S_0 \cdot \Delta T; \quad \Delta V = 3\alpha \cdot V_0 \cdot \Delta T$$

### Change of state

When heat is transferred to a body, its temperature increases. But when the temperature of a body changes, it can **change** its **state** of aggregation.

**During a change** of state, the **temperature** of the body remains **constant**, since the energy transferred to the body is used in rearranging its particles (breaking bonds).

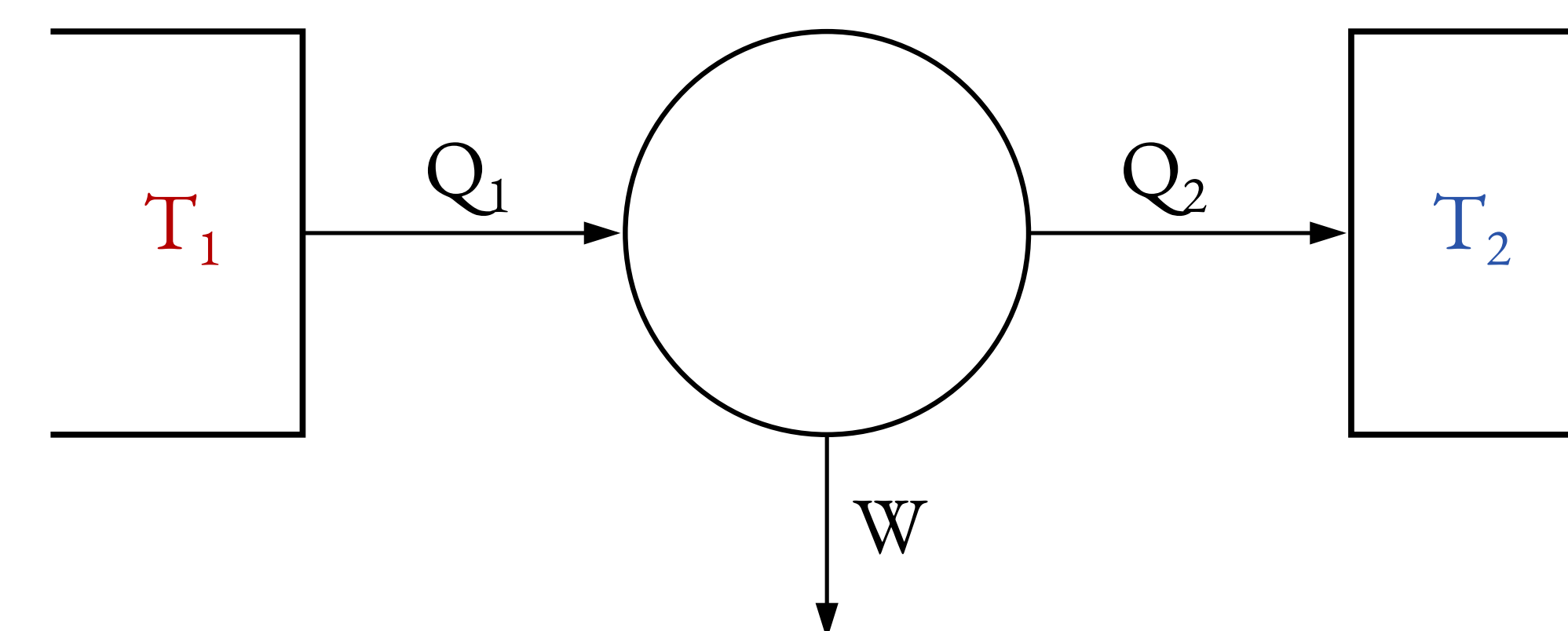
The amount of heat  $Q$  needed to change the state of a substance depends on the substance and its mass  $m$ , through the equation:

$$Q = m \cdot L,$$

where  $L$  is the **latent heat**, which represents the amount of energy needed by the substance to change its state. In the **SI** it is measured in  $\text{J/kg}$ .

## Heat engines

A **heat engine** is a system that works **periodically** between two foci at a different temperature, transforming part of the heat absorbed from the hot source in work and releasing the other part to the cold sink.



**Figure 1.** Diagram of a **heat engine**. The engine absorbs heat from the hot source  $T_1$  and releases heat to the cold sink  $T_2$ , producing work:  $Q_1 = W + |Q_2|$ . Adapted from [https://commons.wikimedia.org/wiki/File:Carnot\\_heat\\_engine\\_2.svg](https://commons.wikimedia.org/wiki/File:Carnot_heat_engine_2.svg).

### Thermal efficiency

The **thermal efficiency**,  $\eta$ , is defined as the quotient between *benefit* and *cost*:

$$\eta = \frac{\text{Work obtained}}{\text{Energy consumed}}$$

For an **engine**:

$$\eta = \frac{W}{Q_1} = \frac{Q_1 - |Q_2|}{Q_1} = 1 - \frac{|Q_2|}{Q_1} < 1$$

It can be demonstrated that the thermal efficiency of an **ideal thermal engine** (called **Carnot engine**) depends only of the temperature of both foci:

$$\eta_{\text{ideal}} = 1 - \frac{T_2}{T_1},$$

which is the maximum efficiency that can be obtained from a thermal cycle operating between two sources with these temperatures.

### Internal combustion engine

It is a **thermal engine** of **internal combustion** produced by an electric spark. It can be considered at a **constant volume**. The most used internal combustion engine is the **four-stroke piston engine** (gasoline), being the **Otto cycle** the most used approximation:

