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** ($1\,\mathrm{J} = 1\,\mathrm{kg\,m^2\,s^{-2}}$).

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:

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

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:

$$\mathrm{PE_g} = mgh,$$

where $h \ll R_\mathrm{E}$ (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:

$$E_\mathrm{m} = \mathrm{KE} + \mathrm{PE}$$

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: $Q_\mathrm{released} + Q_\mathrm{absorbed} = 0$.

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

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** ($1\,\mathrm{W} = 1\,\mathrm{J/s}$), being the **horsepower** ($1\,\mathrm{CV} \approx 735\,\mathrm{W}$) another typical unit.

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

$$1\,\cancel{\mathrm{kW}}\,\cancel{\mathrm{h}} \cdot \frac{1000\,\mathrm{W}}{1\,\cancel{\mathrm{kW}}} \cdot \frac{3600\,\mathrm{s}}{1\,\cancel{\mathrm{h}}} = 3.6\times10^6\,\mathrm{W\,s} = 3.6\times10^6\,\mathrm{J}$$

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 ΔT of that mass is given by the equation:

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

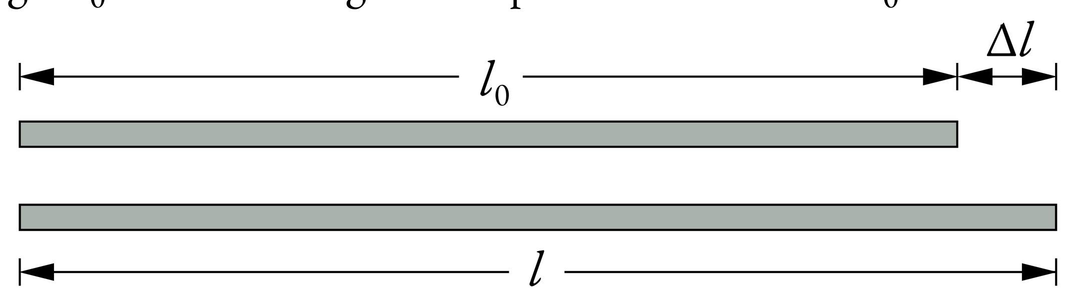
where c is the **specific heat** of that substance, which represents the amount of energy that should be provided to the unit of mass of that substance to increase its temperature one unit. In the **SI** it is measured in $\mathrm{J\,kg^{-1}\,K^{-1}}$.

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 α is the **linear expansion coefficient**, whose units in the **SI** are $\mathrm{K^{-1}}$. 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 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.

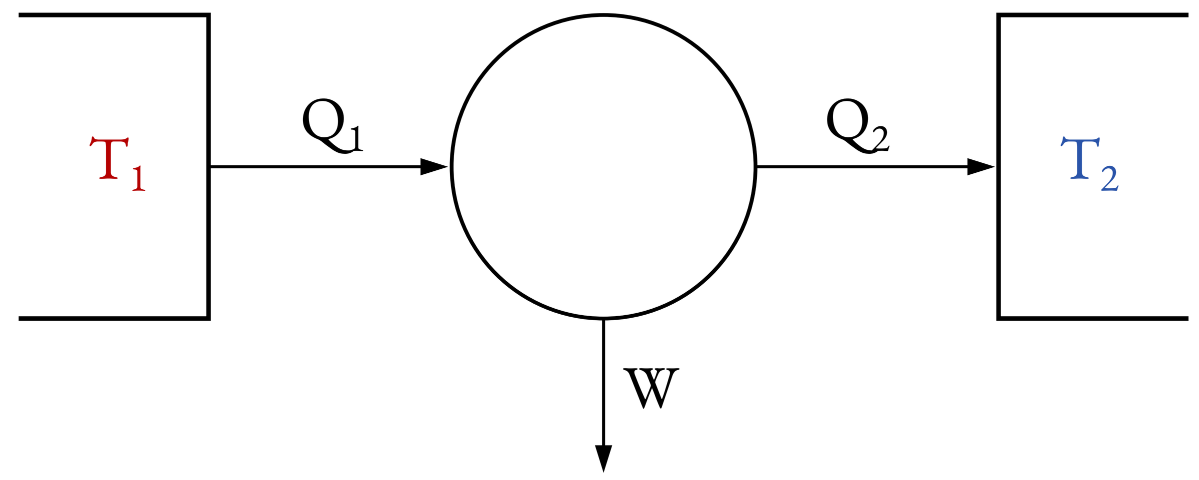


Figure 1. Diagram of a **heat engine**. The engine absorbs heat from the hot source T_1 and releases heat to the cold sink T_2, producing work: $Q_1 = W + |Q_2|$. Adapted from `https://commons.wikimedia.org/wiki/File:Carnot_heat_engine_2.svg`.

Thermal efficiency

The **thermal efficiency**, η, 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:

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

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: