

HEAT AND TEMPERATURE



Thermal and heating phenomena are part of the physical phenomena which we meet in our daily lives. We know that Heat and Temperature are nouns which are part of everyday language and that they are rarely used in a scientifically correct manner. They are frequently identified or used in circular definitions in which one refers directly to the other as a synonym. This is the mistake which is made when we say that the temperature measures "*how hot it is*", or when a person who has a fever is said to "*be hot*", etc..

At other times heat is identified with some material ingredient of bodies. This is why we close the windows "*so that the heat doesn't escape*", or calories are used as a measure of the undesirable supply of matter, "*the fattening part*", of the foods which people eat.

The contents of this Teaching Unit deal with the most elemental thermal and heating phenomena, defining the fundamental concepts which will permit us both to correctly describe these phenomena and to make qualitative predictions about their development.

The next control takes us to the objectives of the unit.

OBJECTIVES

- To distinguish the concepts of heat and temperature.

- To understand how a thermometer works.
- To understand the effect of heat exchange on the temperature of a body or its state of aggregation.
- To define the concept of equilibrium temperature, and to use it to determine the equilibrium temperatures or calorimetric magnitudes in mixtures of substances with different temperatures.

1.1 Defining concepts

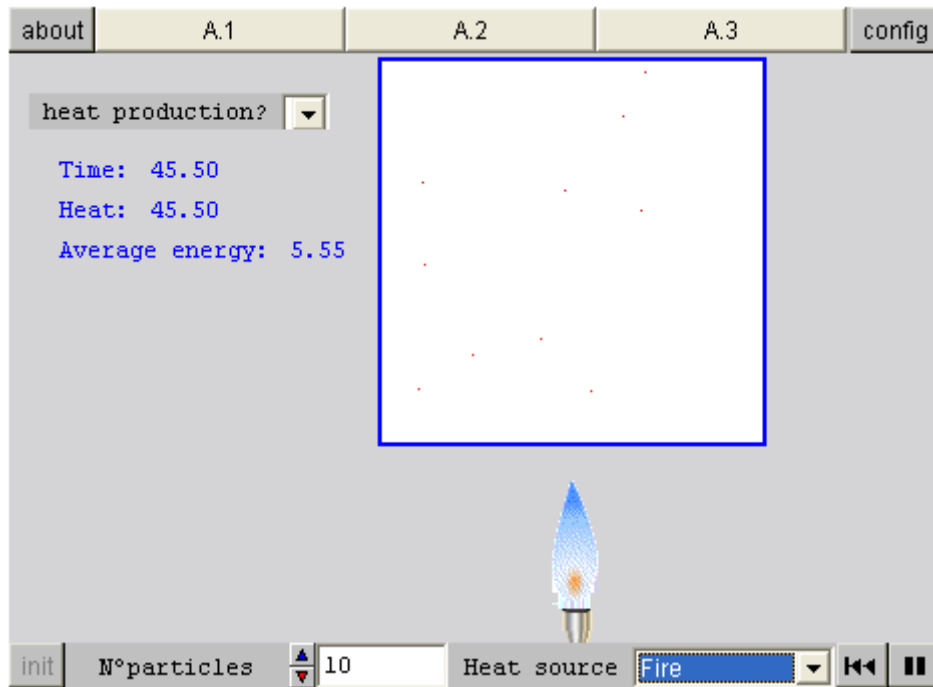
Nowadays we know that the atoms and molecules from which matter is formed are not at rest even though the body they make up is still. In solids the particles vibrate continuously around their point of equilibrium; in fluids they move freely, although they are confined to a determined volume; in gases they move freely, occupying all the space available.

We will call the sum of all the energy of all the particles which make up the body, thermal energy. Temperature is the average value of the kinetic energy of these particles.

We all know that bodies can be heated (increasing their internal energy) or cooled (losing internal energy). The energy gained or lost in these processes is heat.

In the following visual we illustrate the concept of thermal energy, temperature and heat with the example of a gas which we can heat in different ways.

The controls A.1, A.2, A.3 are for guided activities to make the best use of the visual.



A1: Select fire as the source of heat and click on play. Watch the variation of energy for a minute. Click on init and select the friction system before you click on play again. What differences can you observe between the two ways of heating up?

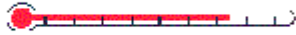
A2: Choose fire as the source of heat. Click on play until the temperature (average energy) is equal to 5 units. Write down the time taken. Click on init and double the number of particles. What can you observe regarding the new temperature that is reached? Has the gas gained a different amount of thermal energy than in the previous case?

A3: Use your notebook to do the following calculations and use the visual to verify your results. If the number of particles increases from 10 to 50, how does the increase of the temperature change when we heat it up for the same amount of time? Does the answer depend on the type of heat source?

1.2 The thermometer

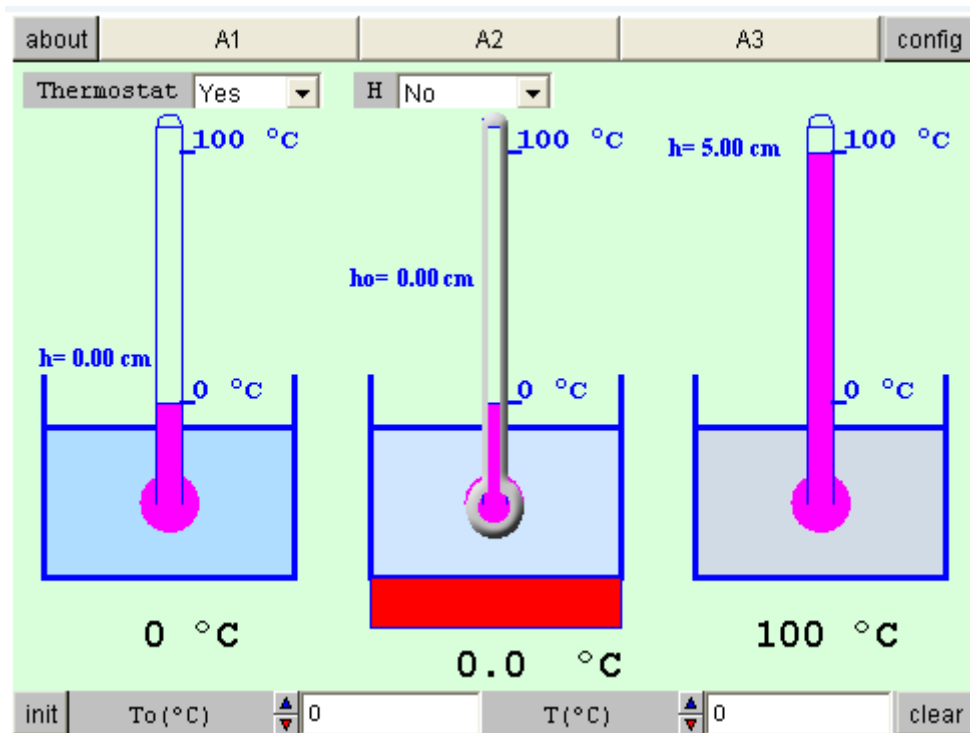
The definition which we have given of temperature is of little practical value as it is not possible to measure the energy of each particle to find the average value. Fortunately, **bodies have observable properties which vary with the temperature.** The effects of the variation of the temperature of a body on some of its characteristic magnitudes, like its length, its volume or its electrical

resistance in the case of a conductor, are well known.



It is this circumstance which is taken advantage of in order to make a thermometer, **making the value of the magnitude used, called thermometric, coincides with the corresponding temperature.** In this way, in the familiar mercury thermometer the height of the column of mercury is made to correspond to the temperature, or in the case of digital thermometers an electric circuit is used in which the electrical resistance is very sensitive to variations in temperature.

In the following visual we initially present three identical thermometers: one of them is set at 0°C (the temperature at which water freezes); another thermometer is set at 100°C (boiling point for water). The third thermometer is set at a temperature of T_0 , from -10°C to 100°C , which can be selected by the user. Using control T we can choose the temperature of the device with a constant temperature, thermostat, into which we will put the thermometer to measure its temperature; using the corresponding control we can put the thermometer in the thermostat or not. A fourth control, H, permits us to see the height of the column of fluid when the thermometer is in the thermostat.



A1: Change the temperature of the thermometer in the middle and try to find the mathematical relation between the initial temperature and the height reached by the thermometric liquid. To find out the relation, fix any two values of T_0 and write down these values together with the corresponding heights. As $T-H$ is a linear relation of the form $T=a \cdot H+B$, replace T and H with the values that you have just written down and solve the system of two equations to find out the values of the coefficients a and b .

A2: Once you have fixed the value of T_0 , select a value of $T > T_0$ for the thermostat. Place the thermometer inside and note the height of the liquid column. Verify the relation you discovered before. Repeat the process for a temperature $T < T_0$.

A3: As a summary of the previous activities, and as a final conclusion, write a mathematical relation that can be applied to any thermometer that uses linear dilation as a thermometric process.

1.3 Absolute temperatures

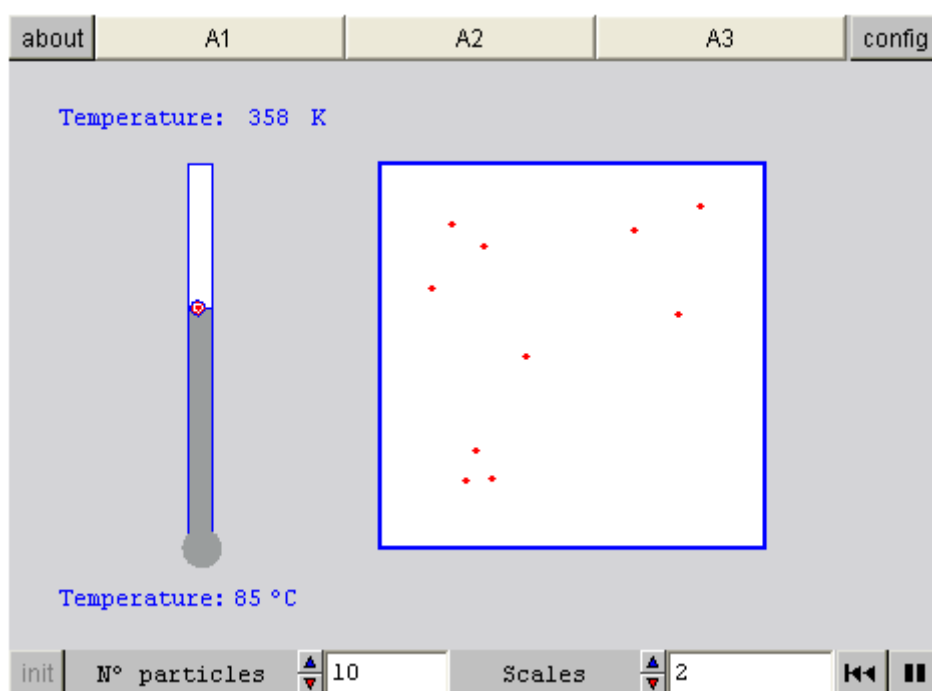
In the Celsius scale we use the temperature at which ice melts as the value zero. All lower temperatures are recorded as negative. Can the temperature reach any negative value? Obviously not; when the particles which make up the body are at rest the body cannot get any colder. At present we know that

this state cannot be reached, but it serves to define the lowest temperature possible.

We will call the temperature which corresponds to the lowest average kinetic energy of the particles in a body, absolute zero.

Of the scales which use absolute temperatures the best known, recognized by the *Système d'Unités International*, is the Kelvin scale.

In the following visual we illustrate the correspondence between both scales by observing what happens to a gas as the temperature changes.



A1: In the visual you can see the agitation of gas particles in accordance with the temperature. Observe that the particles do not all have the same speed. The temperature corresponds to the mean value of the agitation. Decrease the value of the temperature by dragging the red dot on the thermometer. What happens to the movement of the particles? As we move towards the absolute zero of temperature, what condition do the particles come near to? Would your answer change with a different number of particles?

A2: Choose the two scales option. Now you can see the temperature in degrees Celsius and Kelvin. Calculate the difference between these two temperatures and see if it changes when we change the value of the temperature.

A3: If you increase the temperature as much as the visual will allow, the agitation of the particles increases. This thermometer is, of course, limited by the size of its column,

but we could always imagine larger thermometers. Think about this: is there an upper limit for temperatures? Before you answer, look up the temperature of the nuclei of stars in some encyclopaedia.

1.4 Conclusions about the concepts of thermal energy, temperature and heat

Basic concepts:

- **Thermal energy** is the sum of the energy of all the particles which make up a body.
- **Temperature** is the average value of the kinetic energy of the particles of a body.
- **Heat**, which can be produced and transmitted in different ways, is the energy which we supply to, or receive from, a body in the processes in which it varies its internal energy.

How a thermometer works:

Thermometric properties are the observable magnitudes of a body which vary with its temperature: length of a body, resistance of a conductor.... In a mercury thermometer the thermometric property is the height of a column of mercury.

There are different temperature scales:

On the **Celsius scale**: the value 0 corresponds to the melting point of ice and the value 100 to the boiling point of water.

On the **Kelvin scale** the value 0 is a temperature of absolute zero, the temperature at which the particles of a body have the least amount of vigour possible.

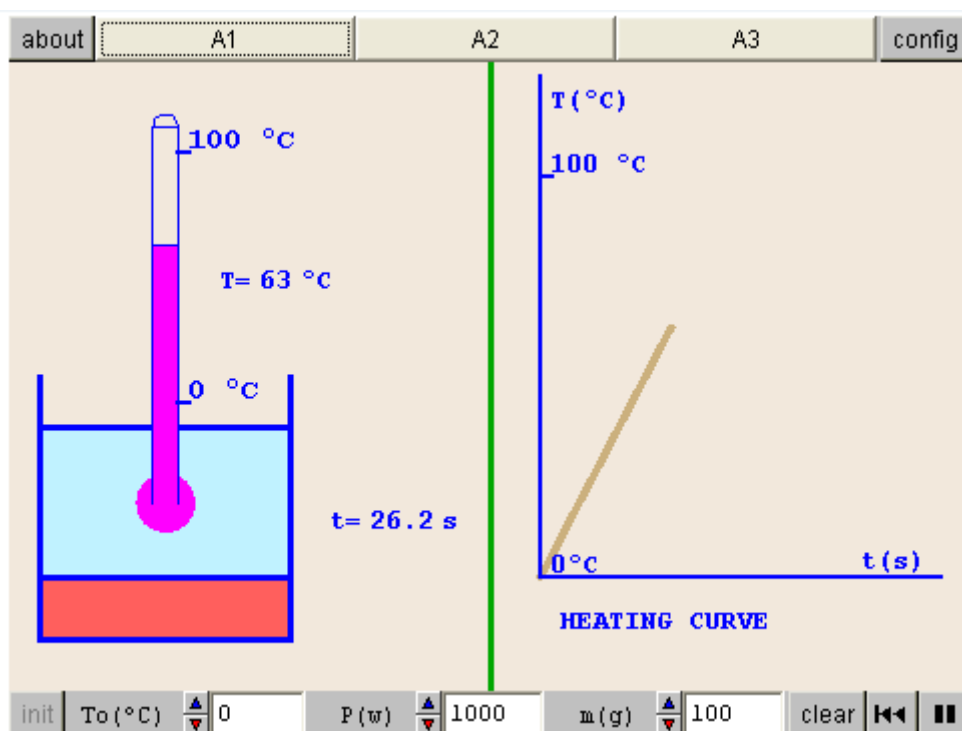
Kelvin temperature= Celsius temperature +273

2.1 The heating curve

Once we have understood the notion of heat and temperature, and how we can measure the latter, we could ask ourselves how bodies are heated. Is the increase in temperature proportional to the energy which we supply in the form of heat?

In the following visual we deal with these questions. We have a substance which is heated by a heater the power of which, in W , we can select with the appropriate control; we can also select the mass of the substance we are heating, as well as its initial temperature.

Using a thermometer we can follow the increase in the temperature of the substance, and the time taken, in the graph on the right temperature is plotted against time (the heating curve). In this visual we have chosen water as the substance to be worked with as it is easy to understand.



A1: Set the initial temperature to 0 °C , choose a value of the mass, 100 grams, for example, and study the relative position and shape of the heating curves that are drawn when you click on play. One way to compare them would be to establish the time taken to reach a given temperature.

A2: Carry out an analogous procedure, but this time compare the curves when the mass of water is changed and the power of the heater is kept fixed.

A3: Repeat the previous activities changing the value of the initial temperature.

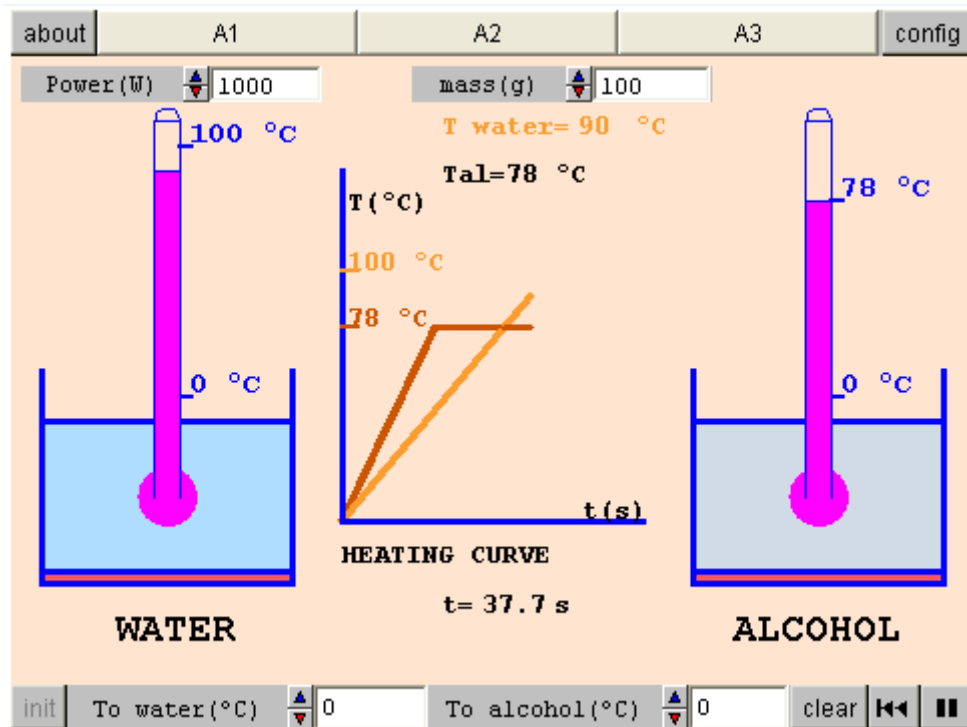
2.2 Specific heat

In the previous visual we used water. Would we have got the same results with other substances?

We know, for example, that when we put a metal spoon into a plate of hot soup its temperature quickly rises, something which doesn't happen if it is a wooden spoon. This observation and others like it led to a characteristic magnitude of a body being defined according to its nature, specific heat.

Specific heat is the necessary energy that the unit mass of a body needs to exchange with the environment in order to vary its temperature by one degree; its units are $\text{J/kg } ^\circ\text{C}$ in the Système International, although in the laboratory it is more usual to use $\text{calorie/g}^\circ\text{C}$, where **calorie is the heat necessary to raise the temperature of one gram of water by one degree.**

In the following visual we compare heating water with heating ethyl alcohol.



A1: Repeat the activities from the previous visual. Now the initial conditions (power, mass and initial temperature) of each simulation are the same for the alcohol and water. Are the observed heating curves also the same?

A2: The heating curves are obviously different for different substances even though linearity is maintained. How can this behaviour be explained? Calculate the specific heat for alcohol, knowing that for water it is $1 \text{ cal/g}^\circ\text{C}$. In order to do this, heat up the same quantity of water as alcohol, in such a way that the temperature of water increases by 10°C . Think about how many calories you have used and how many are needed to make a gram of alcohol raise its temperature by one degree.

A3: You may have noticed in the previous activities that the heating curve is not a straight line, after some time it stops ascending and becomes parallel to the time axis. What does this change in behaviour mean?

2.3 The mechanical equivalent of heat

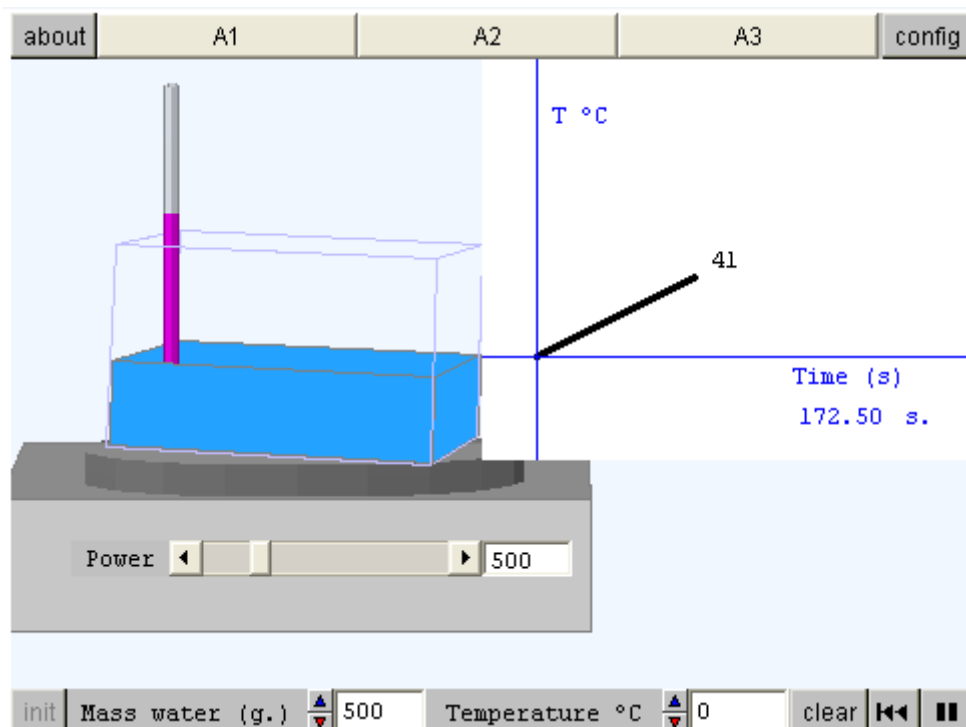
Although the calorie is a very practical unit because it permits the measurement of heat by its thermal effect on water and is easy to measure, this unit of measure has the defect of being different from the ones we use in the rest of Physics to measure any increase in energy. For example in the toaster

electrical energy is converted into heat. How can we make the electrical energy correspond to the heat generated.



We all remember that the SI unit of energy is the joule. So, generalizing on the previous example: **How many joules are equivalent to a calorie?**

In the following visual we answer this type of question. An electric heater with a known power in watts (remember that a watt is one joule per second), will supply electrical energy to a container of water. Let's suppose that the system is appropriately insulated so that all the energy of the heater is used to heat the water, considering that used in the air and in the container itself as negligible.



A1: Turn on the heater with a power of 2000 w. Note the time to taken for the water to reach 100°C. Repeat the process for 1000 w and 500 w. What is the difference of times observed due to? What expression would you use to measure the energy produced by the heater?

A2: In the previous cases, how would you calculate the heat absorbed by the water? Calculate this value and compare it with the result from the previous activity to determine the mechanical equivalent of a calorie.

A3: Calculate the minimum time for the heater to raise the temperature of 1000 grams of water to 100°C. What if the initial temperature were 30°C?

2.3 Conclusions about specific heat and the mechanical equivalent of heat

The rise in temperature of bodies when they are heated is approximately proportional to the energy supplied.

A commonly used unit to measure this energy (heat) is called the **calorie**: *the heat necessary for a gram of water to increase its temperature by 1°C.*

Not all bodies heat up in the same way. **Specific heat** is the property of bodies which measures this difference and can be defined as *the heat necessary for the unit mass of a body to increase its temperature by 1°C.*

The heat lost or absorbed by a body can be measured by the expression:
 $Q = m \cdot c \cdot (T_f - T_o)$ where m is the mass of the body, c its specific heat, T_f its final temperature and T_o its initial temperature.

A calorie is equivalent to the transfer of 4.18 j of energy, which permits us to write all the former expressions in SI units. Thus, the specific heat of water is
 $C_a = 1 \text{ cal/g}^\circ\text{C} = 4180 \text{ j/kg}^\circ\text{C}$

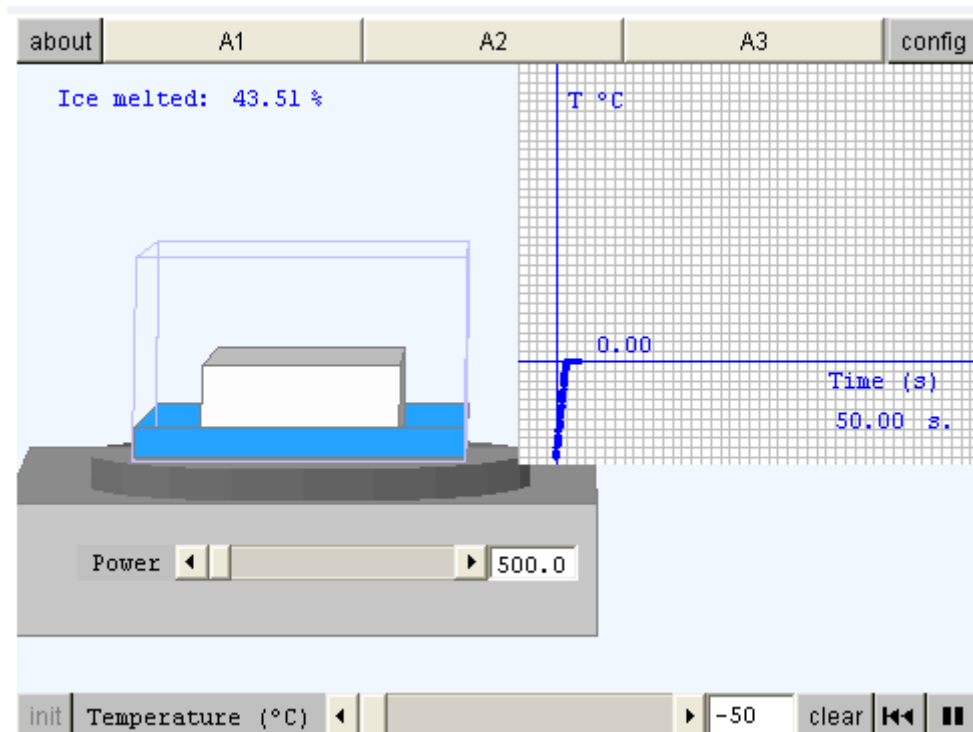
3.1 Change of state temperaturas

In the heating curves of a body it seemed that the increase in its temperature was proportional to the energy absorbed. However, there are cases in which this rule does not apply. Especially when the body is changing its state of aggregation. We all know that matter basically presents itself to us in three

possible states: solid, liquid and gaseous. Each of these states is due to the existence of different binding energies among the molecules of a body. When the body changes state we are altering this form of internal energy instead of increasing the temperature.

How is this phenomenon translated onto the heating curve of a body? To study this we will observe the case of a block of ice of 100 g mass which we progressively heat until we convert it into steam.

We should tell you that in this visual, for the sake of simplicity, we are ignoring the quantity of water which evaporates while the temperature increases from 0°C to 100°C. We should also take into account that the fusion and boiling point temperatures observed are only true at the pressure of one atmosphere and with distilled water. The change of state temperature depends on the pressure conditions in the environment where the substance is and the latter's degree of purity.



A1: Turn on the heater by clicking on play. The heating curve suffers two important modifications on its way. What is happen when these modifications occur? What are the temperatures? Change the initial temperature of the block of ice. What is the influence of this change on the graph?

A2: Observe the branches of the graph in which the temperature is not constant. In which state is the specific heat of water lower? In which state is the specific heat higher?

A3: Watch the visual a couple of times changing the power of the heater. When the temperature is constant, where does the heat from the heater go to? What change of state needs more energy?

3.2 Latent heat in change of state

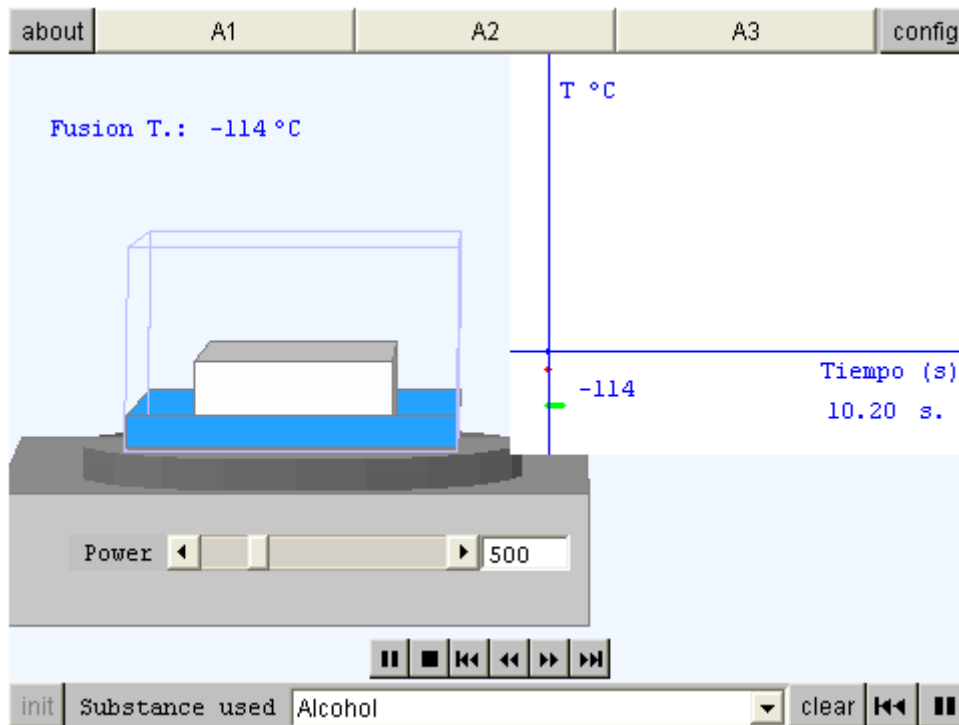
During the transition from one physical state to another, heat, the energy absorbed by a body is not used to increase the agitation (measured by the temperature) of its molecules, but in breaking the bonding among them.



It continues increasing the thermal energy of the body, but not its temperature. So, how much energy is needed to produce this change of phase?

The energy needed to produce a change of phase per unit mass is called latent heat (of fusion or boiling, depending on the case). In the laboratory it is common to measure it in cal/g, but its SI value is measured in j/kg. ***We should not forget the equivalence: $1 \text{ cal/g} = 4180 \text{ j/kg}$***

In the following visual we will measure the latent heat of fusion and boiling of water, heating a block of ice with an electric heater with a known power.



A1: Turn on the heater and note down the times at which the fusion ends, the boiling starts and the boiling ends. What amount of heat produces the fusion? How about the boiling? As the mass is 100 grams, if you divide by 100, you will have the energy necessary to change the state of 1 gram, this is the latent heat of the change of state.

A2: Change the substance used. What differences can you observe among the three graphs? Which substance melts more easily? Which one needs more energy to boil? Order them by their specific heat.

A3: Note the temperatures at which alcohol and mercury melt and boil. As in the first exercise, calculate their latent heats for the changes of state. Can you also calculate their specific heat?

3.3 Conclusions about changes of state

We call the **change of state temperature** of a substance the temperature at which, *although the body absorbs or emits heat, the variation in energy is totally used in changing the physical state of the body*. While this transformation lasts the temperature of the body does not vary.

In general, bodies have a **melting point** and a **boiling point**, although we must remember that these temperatures depend on the outside pressure and the purity of the substance.

We call **the energy necessary for the unit mass of a body, which is already at the appropriate temperature to change its state, latent heat (of fusion or boiling)**.

A well-known example is distilled water

Melting point at 1 atmosphere of pressure: 0°C

Boiling point at 1 atmosphere of pressure: 100°C

Latent heat of fusion: 80 cal/g = 334.400 j/kg

Latent heat of boiling: 540 cal/g = 2.257.200 j/kg

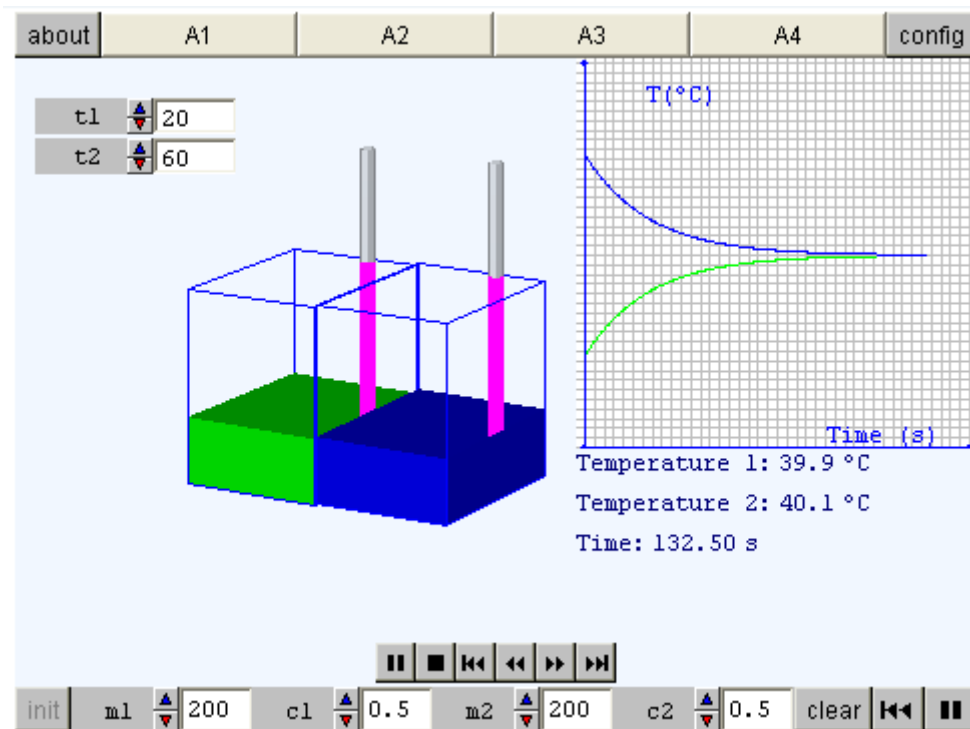
4.1 Equilibrium temperature

We all know that a hot body tends to increase the temperature of the bodies which surround it, while a cold body causes a decrease in temperature around it. In stricter terms we could state that, ***when two substances at different temperatures are near to each other, there is an exchange of energy between them which tends to create thermal equilibrium, which is reached when both temperatures are equal.***

According to the Law of Conservation of Energy the net energy exchange between the two systems and the environment would be zero, and limiting ourselves to the simplest case, which is an ideal case, the situation could be expressed by saying that the heat lost by the hot system as it cools is exactly the same as the heat absorbed by the cold system as it heats up.

In this ideal case we can make another simplification: that we only consider the hot and cold substances and not the containers, which would be considered ideal adiabatic containers, with walls which were perfect thermal insulators; the real life case which is most similar would be a thermos flask or a down sleeping bag.

In the visual we present the two substances exchange heat through the partition which separates them.



A1: Click on play. Change the initial temperatures and repeat the process. Which of the liquids heats up? Which one cools down? What happens in the end? Is the variation of temperature per unit of time always the same? What does the speed of variation of temperature depend on?

A2: Without altering the other parameters, carry out experiments changing the mass of the liquids (decreasing the mass of one and increasing the other). In which direction does the equilibrium temperature move? Which of the two liquids suffers a greater variation of temperature? Which of them absorbs or emits more heat?

A3: Carry out the experiment a few times, changing the value of the specific heat only (increasing this value for one liquid and decreasing it for the other). In which direction does the equilibrium temperature move? Which of the liquids suffers a greater variation of temperature? Which of them absorbs or emits more heat?

A4: If we put together 300 grams of a liquid with a specific heat of $0.7 \text{ cal/g}^\circ\text{C}$ and a temperature of 30°C , with 200 grams of another, with a specific heat of $0.9 \text{ cal/g}^\circ\text{C}$ at 70°C , what will the temperature of equilibrium be? Calculate it in your notebook and verify the results with the visual.

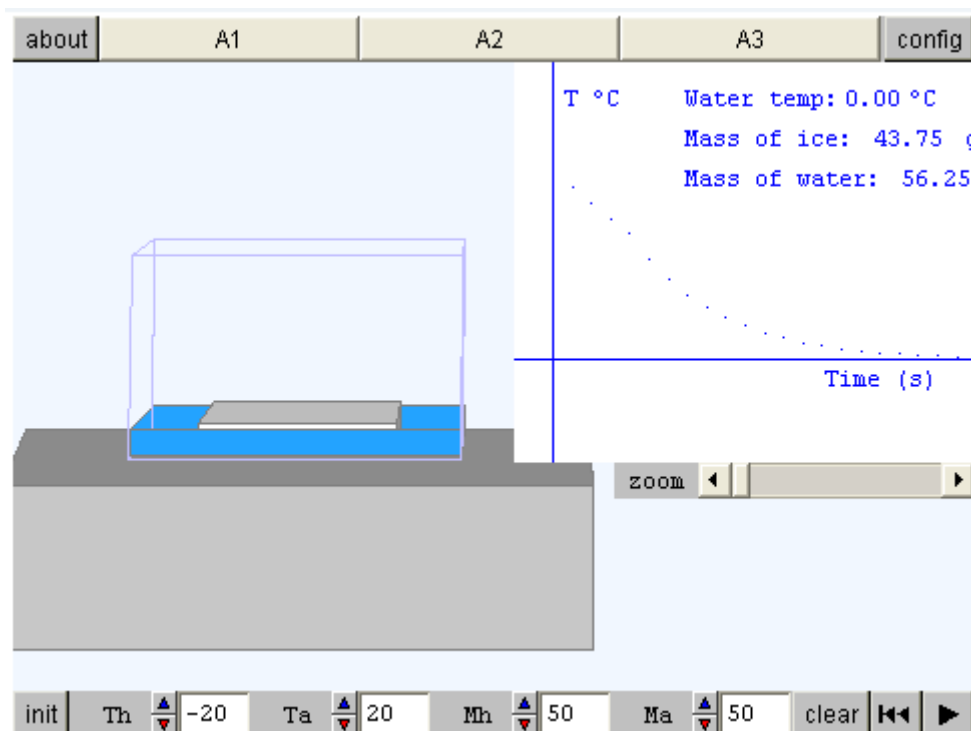
4.2 Equilibrium between substances in different states

Let's suppose we have to consider the case of searching for thermal equilibrium between bodies in different physical states. This would be the case, for example, of a block of ice in a container of hot water.

In phenomena like this we have to consider that the heat lost or gained does not have to be used only in varying the temperature, but that there may be a total or partial change of state of one of the bodies involved.

The law of the conservation of energy will still be valid, but in the use of the energy gained or lost by each body we must count that used in the change of state.

In the visual we are going to study we will use ice and water in variable quantities and with variable temperatures. After carrying out the activities suggested we should be able to predict the equilibrium temperature and the volume of water and ice left when equilibrium is reached. We should note that the time taken to reach equilibrium depends on many external factors, so that the time taken to reach equilibrium in the visual is not necessarily the time taken in real life.



A1: Click on play. Observe the changes in the mass and water as the temperature of the water decreases. Where is energy lost? Where is it gained? What is the energy used for?

A2: Try to find the exact point at which all the ice melts, by varying the mass of the liquid water and its temperature. Then increase the initial temperature of the ice to 0°C.

Can you guess what the final temperature will be? Verify your calculations with the visual.

A3: What values of the parameters will make the final temperature as high as possible? What values will give us the lowest final temperature? What will the mass of ice be in the latter case? Calculate these values in your notebook and verify them with the visual.

4.3 Conclusions about thermal equilibrium

When two bodies which are near to each other have different temperatures, the hotter one emits calorific energy and the colder one absorbs it, until both reach an equal temperature.

In an ideal case, with a system formed exclusively by two bodies isolated from the rest of the universe, *the energy lost by one is equal to that gained by the other.*

The exchange of energy is proportional to the difference in temperature between the bodies. For this reason as the temperatures get closer, the process gets slower.

When the two bodies are in the same state, the equilibrium temperature is determined by: $m_1 \cdot c_1 \cdot (t_1 - t_e) = m_2 \cdot c_2 \cdot (t_e - t_2)$ where m, c and t are the mass, the specific heat and the initial temperature of the hot body (with subscript 1) and the cold body (with subscript 2) while t_e is the equilibrium temperature.

When the bodies present different physical states, the energy exchange equations must take into account the heat used to partially or totally change the state of one of the two bodies.

EVALUATION

Choose the right answer to each question

What do you know about heat and temperature?

- 1 While a body is changing from a solid state to a liquid state, the heat it absorbs

Change of state

- breaks the binding between molecules, and the temperature remains constant
- breaks the molecular binding, and the temperature increases at a constant rate
- is lost. It produces no effect because the temperature remains constant
- Produces an increase of the temperature proportional to the amount of heat absorbed

- 2 Is it correct to believe that the temperature is the amount of heat stored by a body?

- Yes, the temperature measures the average heat of the particles in a body
- Yes, the temperature measures the total heat of the particles in a body
- No, the temperature measures the total agitation of the particles in a body
- No, the temperature is a measure of the average agitation of the particles in a body

3 We could define heat as:

- A fluid that flows from hot bodies to cold ones
- A way in which different bodies interchange energy
- The temperature of a body
- A positive form of energy. Cold is a negative form of energy
- A way of measuring the energy that a body stores

4 When a body absorbs 1 calorie of heat

- Its internal energy has increased by 4,18 J
- Its internal energy has increased by 1°C
- Its internal energy remains constant, and its temperature increases
- Its internal energy has lost 1 calorie, that is, 4,18 J

5 We have 150 grams of water at a temperature of 12 °C in a container with adiabatic walls, so that there is no interchange of heat with the outside; Calculate the equilibrium temperature if we mix 80 grams of water at 84 °C with the water in the container.

- 12 °C
- 84 °C
- 37 °C
- 53 °C
- 40 °C

6 If we have a 50 gram block of ice at -5°C , what amount of heat, measured in Joules, must it absorb to turn into liquid water at 5°C ? If this heat were produced by liquid water at 92°C , how much water would we need?

$c_{\text{e(ice)}} = 0,5 \text{ cal /g } ^{\circ}\text{C}$; $L_{\text{fusion}} = 80 \text{ cal/g}$

- Approximately 1250 J and we need about 500 grams of water
- Approximately 16720 J and we need about 40 grams of water
- Approximately 12750 J and we need about 5 kg of water
- Approximately 625 J and we need about 10 grams of water
- Approximately 18270 J and we need about 50 grams of water

6 Calculate the amount of energy (in Joules) you need to make 300 grams of water at 25°C boil completely. The necessary data are:

$c_{\text{e(water)}} = 4186 \text{ J/kg}^{\circ}\text{C}$; $L_{\text{vapour}} = 2260.4 \text{ kJ/kg}$

- 678120 J
- 772305 J
- 583935 J
- 126545 J
- 94185 J

7 If the column of mercury when the thermometer is put in the melting ice reaches a height of 2 cm, and a height of 8 cm when it is put into boiling water, what height will it reach when it is at 35°C ?

thermometer

- 6.1 cm
- 2 cm
- 5.8 cm
- 4.1 cm
- 8 cm

9 We pour 200 grams of water at 20 °C into a container and 100 grams of another liquid at 50°C. The equilibrium temperature is 30 °C. Determine the specific heat of the liquid in cal/g°C and in J/kg°C

- 0.5 cal/g°C y 2090 J/kg°C
- 1 cal/g°C y 4180 J/kg°C
- 0.25 cal/g°C y 1045 J/kg°C
- 4.18 cal/g°C y 4180 J/kg°C
- 0.75 cal/g°C y 3135 J/kg°C

10 If we wish to heat up 300 grams of water from 10°C to 60°C with a 5000 watt heater, how long will it take?

Heating curve

- 126 s
- 30 s
- 215 s
- 184 s
- 160 s