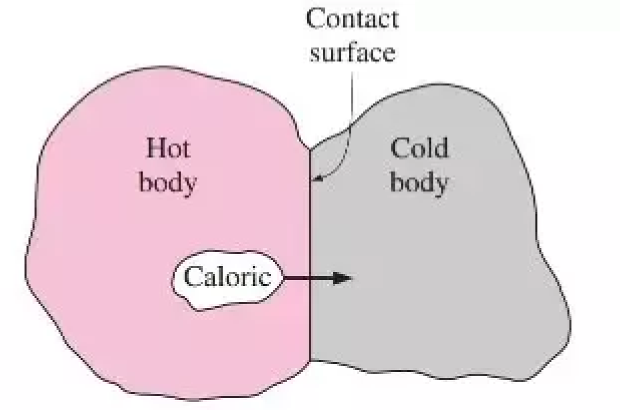
LESSON 6: HEAT and TEMPERATURE

1. Introduction.

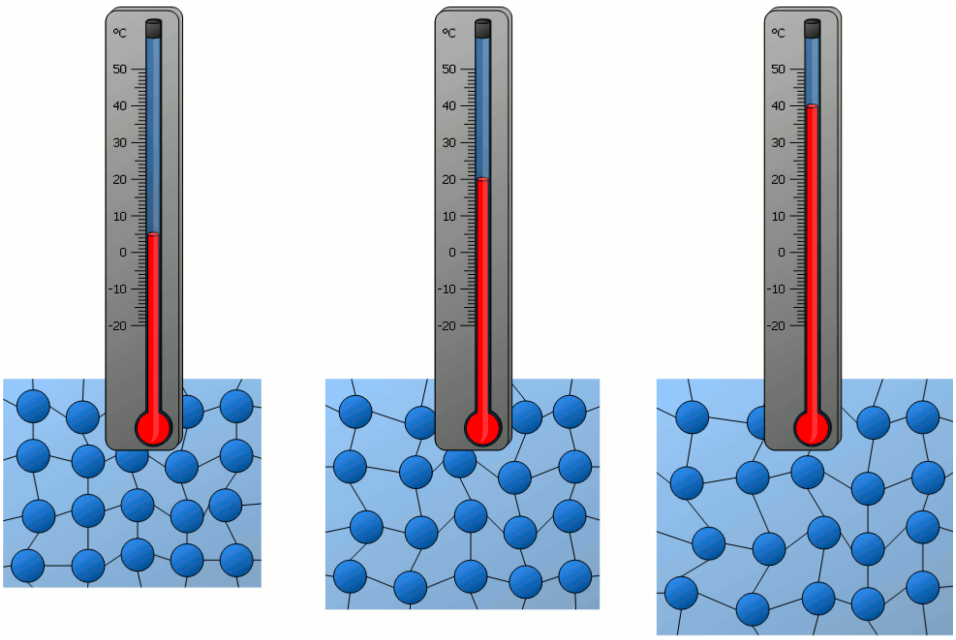
The idea of what is behind the concept of heat has essentially had two main visions along the history.

- The one pointing out the heat to be related to a kind of fluid that was called 'caloric' which basically would flow from regions where its value is major to those where it is minor.



Source: https://www.quora.com/How-is-fluid-mechanics-related-to-heat-transfer [Requested on February the 26th of 2022]

- The one defending that the heat is related to the vibratiry state of motion of the particle conforming a substance.



Source: https://www.tec-science.com/thermodynamics/temperature/temperature-and-particle-motion/ [Requested on February the 26th of 2022]

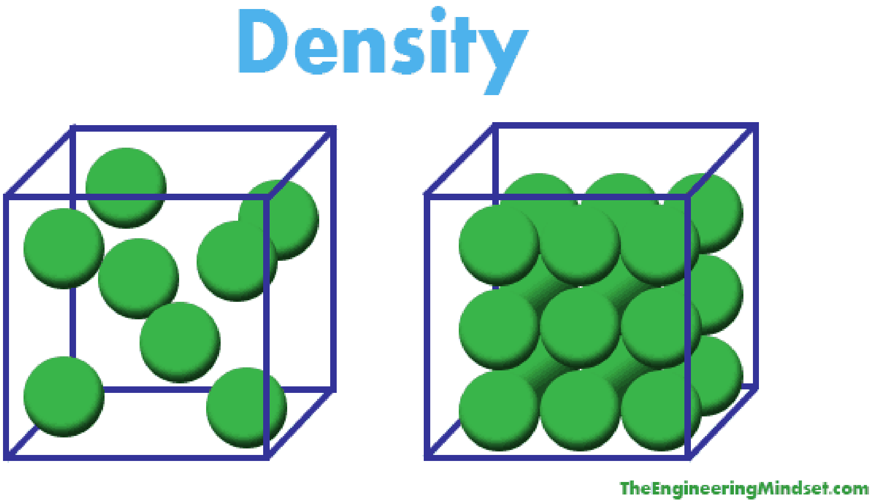
This later was an old idea that was restored by scientists like Galileo Galilei or Robert Hooke during the XVII century. But even though the idea of 'caloric' was kept during most of the XVIII century, and essentially as to explain the heat released or absorbed by some chemical reactions, until Lavoisier showed that this vision can't be sustained anymore. Actually we know that heat is related to the kinetic energy of the particles of a given substance.

2. What is density?

Of course the amount of heat a substance is able to transfer has to do with its density. So, it's worth reviewing what the density is.

The density is just the relationship between the mass and the volume. In other words, the density is the amount of mass per unit of volume.

$$d = \frac{m}{V}$$



Author: Paul Evans; Source: https://theengineeringmindset.com/density-explained/ [Requested on February the 26th of 2022]

In the example above, we can appreciate how the density depends on how many particles we have in a given volume and theis mass. See animation in subsection 2.1 of this link:
http://recursostic.educacion.es/secundaria/edad/4esofisicaquimica/4quincena4/4q4_index.htm

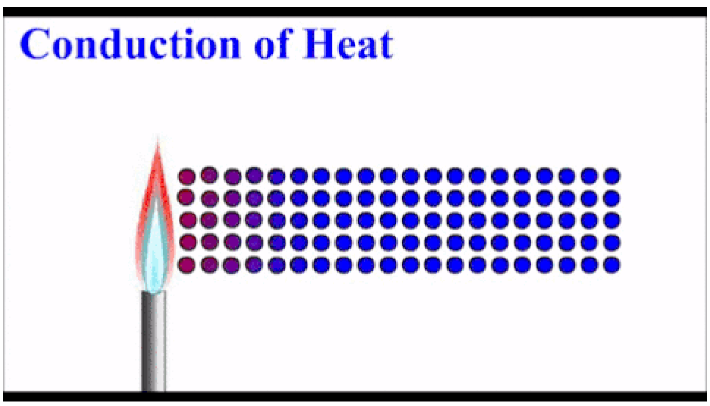
The units of heat in the International System of Units are kg/m^3. **The density of water is 1 g/cm³**.

3. Concept of Heat.

The heat is energy transferred between two bodies or substances at different temperatures.

The usage of thermometers is required to measure the temperatures, key parameters to calculate the heat, but not the only ones.

James Prescott Joule va trobar que hi ha una equivalència entre treball mecànic i calor.



Source: https://gifer.com/en/9vmM [Requested on February the 26th of 2022]

The unit of heat was called calorie [cal] and it was defined as the amount of heat that has to be transferred as to increase one gram of water in one celsius degree (in particular, from 14,5 º to 15,5º).

The the equivalence between the units of heat and the units of work that was found by Joule is:

$$1 \text{ cal} = 4{,}18 \text{ J}$$

3.1. Signs criteria.

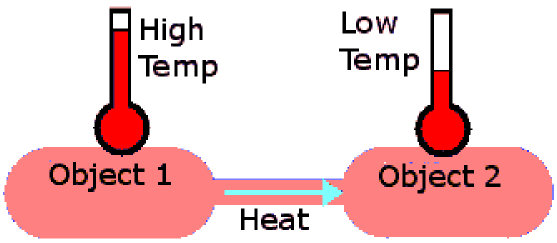
Usually, we convein that when:

- $T_2 > T_1 \Rightarrow \Delta T > 0$ and the body absorbs heat (Q).
- $T_1 > T_2 \Rightarrow \Delta T < 0$ and the body releases heat(Q).

So, heat coming into the body or system is positive while heat coming out from the body or system is negative.

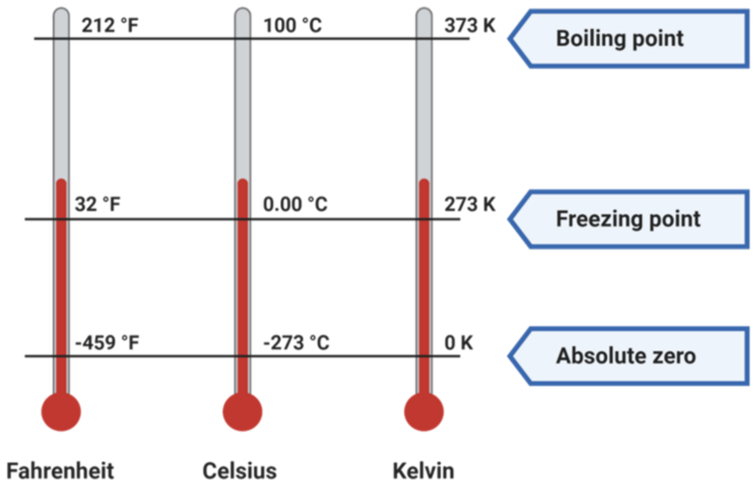
4. Concept of Temperature.

The temperature is a value that can be measured with a thermometer that is related to the mean kinetic energy of the particles from which a substance is made off. When two bodies get in contact with two substances mixed, the direction to which the heat will flow will depend on the value of the temperatures of these two bodies or objects.



Source: http://labman.phys.utk.edu/phys221core/modules/m9/heat.html [Requested on February the 26th of 2022]

The temperature can be measured in 3 different units:



Author: Emeka Udenze; Source: https://commons.wikimedia.org/wiki/File:Temperature_Scales.png Requested on February the 26th of 2022]

We are not going to use the Farenheit scale and in case we have to convert Celsius to Kelvin degrees or vice versa we can just use the next relationship: **T(K) = T(ºC) + 273[1]**.

You can observe how the Celsius scale is just a centigrade scale, in the sense that it just divides in un hundred equals spaced units the range between water's freezing and boiling points.

5. Relationship between heat and temperature.

The heat transferred to a body or substance to increase its temperature from T_1 to T_2 depends on:

- $\Delta T = T_2 - T_1$, the difference between the initial and the final temperature.
- m, the total mass of the body or substance.
- c, the specific heat, a parameter whose value is unique for each and every material and express the capacity of a substance transferring through it[2].

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

5.1. Specific heat.

The values of specific heat are determined experimentally and we can usually pick them up from tables. It's worth paying attention to which their units are, because it could change from table to table.

These units could be $J \cdot Kg^{-1} \cdot K^{-1}$ or $cal \cdot g^{-1} \cdot K^{-1}$, among others.

Check how its value for water changes depending on the state (liquid, ice or steam).

Also, each and every chemical element has its proper specific heat value, which can be checked from this highly recommended web page:

https://ptable.com/

Table 1: Specific Heats of Common Substances

Substance	Specific Heat Capacity, C (J/g·°C)
Water (liquid)	4.184
Ice at 0°C	2.010
Steam at 100°C	1.996
Aluminum	0.902
Chromium	0.461
Lead	0.128
Magnesium	1.020
Mercury	0.140
Tin	0.213
Zinc	0.387

Author:https://www.chegg.com /;
Source: https://www.chegg.com/homework-help/questions-and-answers/following-table-lists-specific-heat-capacities-select-substances-specific-heat-capacity-su-q45192063
Requested on February the 26th of 2022]

[1] We will see where this value comes from in the last subsection (6.2.3)
[2] Which of course depends on its inner structure and state (solid, liquid or gas).

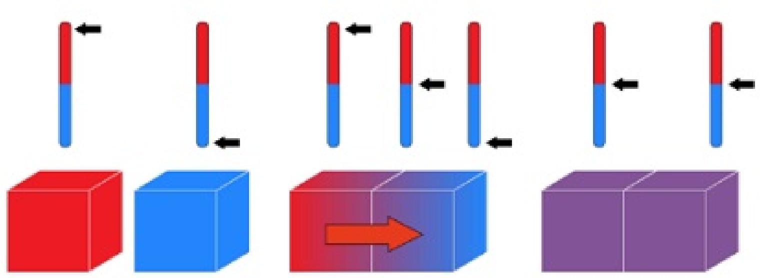
5.2. Thermal balance.

When two bodies or substances at different temperatures get in contact or are mixed a thermal balance will be reached after a given time. Because we know that essentially the heat will flow from the 'hot' to the 'cold' body, we can express its transfer as:

$$Q_{lost} = Q_{gained}$$

whereas the heat lost by the 'hot' body or substance will be negative and the heat gained by the 'cold' one, positive, attending to the sign criteria exposed in section 3.1.

The thermal balance will be reached when, after a while, both bodies or substances reach the same temperature.



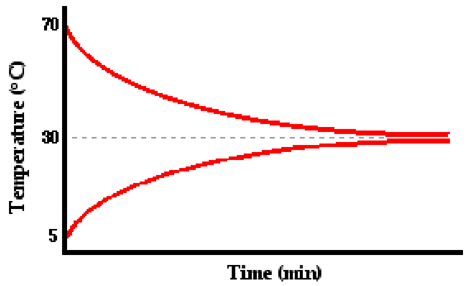
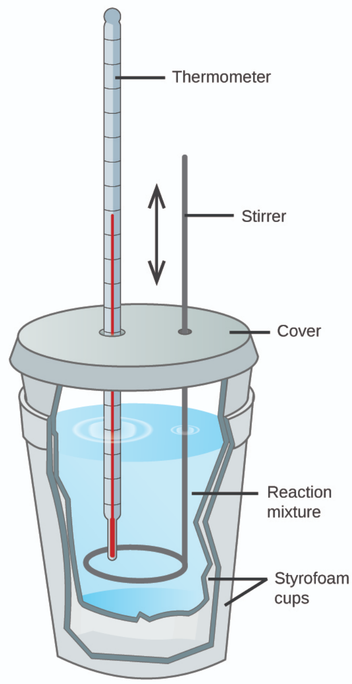


Image on the left, Author: Ahmad Noor U Deen Source: https://whatmaster.com/what-is-thermal-equilibrium/
Image on the right, Source: https://www.physicsclassroom.com/Class/thermalP/u18l1d.cfm [Both requested on February the 26th of 2022]

5.3. Method for determination of specific heat values by the method of mixtures.

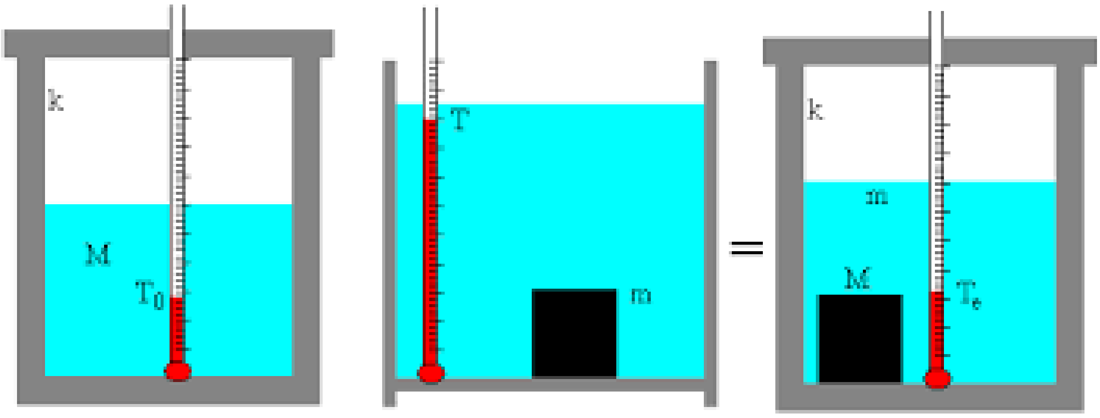


In order to determine the specific heat of a solid a calorimeter will be used. A calorimeter is a recipient made of a very heat insulating material that can be closed in almost an hermetic way, so that any heat transfer process inside of it will remain in it.

The process will follow 3 steps:

1. You weigh a given amount of water (M) and measure its temperature (T_0).
2. You weigh a given amount of a solid (m) and measure its temperature (T), which could be higher if you introduce it within a calorimeter with hot water and wait until the thermal balance is reached.
3. You mixed the 'cold' water from step 1 with the 'hot' solid from step 2 into the calorimeter and measure the final temperature once the balance has been reached (T_e).

Author: Rice University; Source:https://opentextbc.ca/chemistry/chapter/5-2-calorimetry/ Requested on February the 26th of 2022]



Source:http://www.sc.ehu.es/sbweb/fisica/estadistica/otros/calorimetro/calorimetro.htm Requested on February the 26th of 2022]

Then you apply the thermal balance equation:

$$Q_{\text{lost by the solid}} = Q_{\text{gained by water}} + Q_{\text{gained by the calorimeter}}$$

$$m \cdot c_s \cdot (T_e - T_0) = M \cdot (1\ cal) \cdot (T_e - T) + c_{cal} \cdot (T_e - T)$$

whereas:

- c_s is the specific heat of the solid.
- c_c is the specific heat of the calorimeter, whose value can be determined experimentally as well by mixing two volumes of water at different temperatures.

$$c_s = \frac{(M + c_{cal}) \cdot (T_e - T)}{m \cdot (T_e - T_0)}$$

Example of the steps to follow for the specific heat of the calorimeter to be determined:

1. We measure 200 mL of water twice in test tubes.
2. We pour it into two beakers.
3. We measure the temperature of one of the glasses, which will become cold water.
   - We get T_{cold} = 20,7 ºC.
4. We heat the water in the other glass with a resistance until it reaches a temperature that will be that of hot water.
   - We get T_{hot} = 90 ºC.
5. We mix the cold water and the hot water in the calorimeter and, once the thermal equilibrium is reached, we measure the final temperature.
   - We get T_{final} = 56,8 ºC.
6. We are now ready to proceed with calculations.

$$m_{H_2O} \cdot c_{H_2O} \cdot (T_{final} - T_{hot}) + m_{H_2O} \cdot c_{H_2O} \cdot (T_{final} - T_{cold}) + c_{cal} \cdot (T_{final} - T_{cold}) = 0$$

200 g·4,18J/g·ºC·(56,8ºC-90ºC) + 200 g·4,18J/g·ºC·(56,8ºC-20,7ºC)n + c_{cal}·(56,8ºC-20,7ºC) = 0

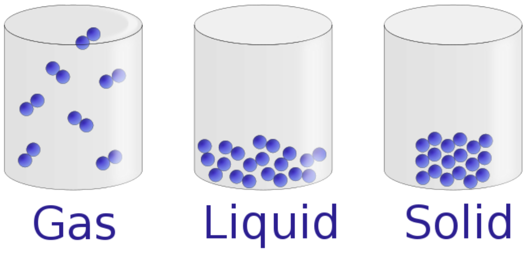
c_{cal} = -67,16 J/ºC

Look at this video to figure out how the specific heat of a metal can be determined:

- YouTube video from the Professor Dave Explains channel, Heat Capacity, Specific Heat, and Calorimetry: https://www.youtube.com/watch?v=yhNHJ7WdT8A.
- YouTube video from the 7activestudio channel, CALORIMETRY:
  - https://www.youtube.com/watch?v=xUNoA-fh4JM
  - https://www.youtube.com/watch?v=WtIG3zWaTK8

6. Changes of states.

You know matter can be organized in essentially 3 main states depending on the forces acting between their constituents (atoms, ions or molecules: solid, liquid or gas.



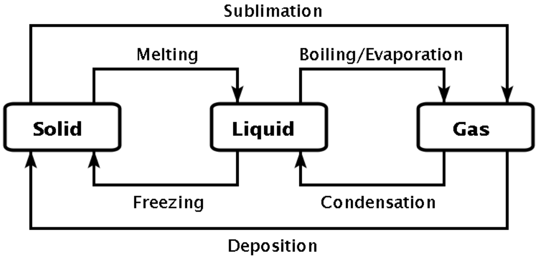
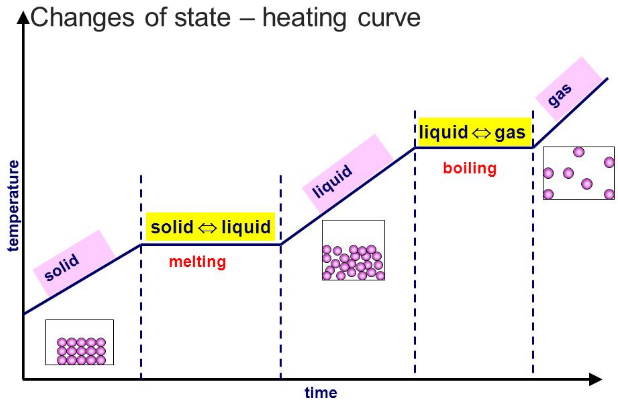
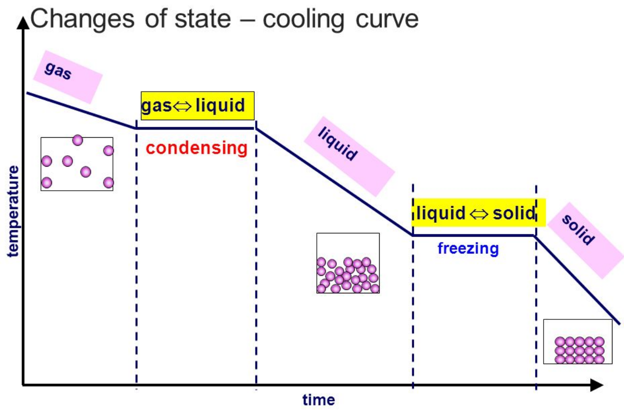


Image on the left, Author: Yelod, Source: https://commons.wikimedia.org/wiki/File:States_of_matter_En.svg
Image on the right, Author: AnyFile, Source: https://commons.wikimedia.org/wiki/File:Phase_changes.svg [Both requested on February the 27th of 2022]

During the process of state change all the heat transferred is used as energy to break or bond the particles. Because of that, the state of vibration of the particles during the state changes doesn't change and thus the temperature remains constant.





Author: Antonia Morton, Both images are extracted from Heating and Cooling Curves presentation on https://slideplayer.com/slide/9405538/ [Requested on February the 27th of 2022]

We all must know that

- the melting/condensation temperature for water is 0 ºC and
- the boiling/evaporation/condensation temperature for water is 100 ºC.

Look at these videos as to reinforce these concepts:

- YouTube video from the Professor Dave Explains channel, Phase Changes, Heats of Fusion and Vaporization, and Phase Diagrams: https://www.youtube.com/watch?v=oc0ypeDELb0.
- YouTube video from the SPM Malaysia IPTV chanel, [4.3] Cooling and Heating curve of naphthalene: https://www.youtube.com/watch?v=tkhkaJLdesM.
- YouTube video from Jessica Donovan channel, Heating and Cooling Curves: https://www.youtube.com/watch?v=_-ea_OH9xvQ.
- YouTube video from AboodyTV channel, HEATING CURVE - How to Read & How TO Draw A Heating Curve - [AboodyTV] - Chemistry: https://www.youtube.com/watch?v=isOtNOo1g68.

6.1.Latent heat.

In the stages of the heating or the cooling curves for which the state of matter remains, the heat transferred to raise the temperature a given range can be calculated as we saw in section 5, just paying attention to use the proper specific heat value depending on the specific state of matter the substance is in.

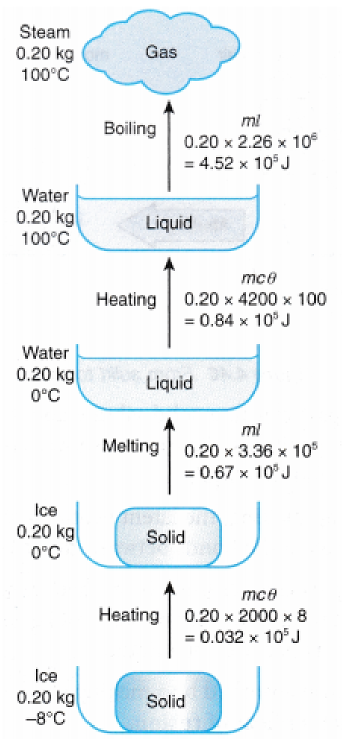
But during the change of state, as long as the temperature remains constant, it is not possible to calculate the heat transferred from the change in the temperature. So, in these transitions, the heat transferred has to be calculated from the latent heat instead of calculating it from the specific heat in a way that indeed it results simpler.

The heat absorbed or released per unit mass in a change of state is a constant for each substance and for each change of state it is known as the latent heat of change of state, L. The amount of heat put into play in a change of state is:

$$Q = \pm m \cdot L$$

whereas L is the latent heat and has a different value for each state change.

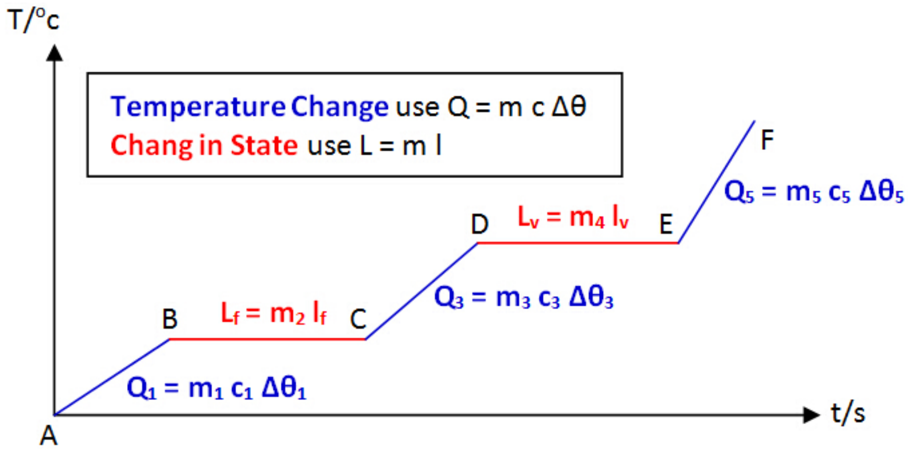
Substance	Melting point / °C	Specific latent heat of fusion, / J kg⁻¹	Boiling point / °C	Specific latent heat of vaporisation, / J kg⁻¹
Water	0	3.36×10^5	100	2.26×10^6
Mercury	−39	1.14×10^4	357	2.96×10^5
Ethanol	−114	1.08×10^5	78	8.55×10^5
Gold	1063	6.28×10^4	2808	1.72×10^6
Copper	1083	2.07×10^5	2566	4.73×10^6
Lead	327	2.32×10^4	1750	8.59×10^5
Nitrogen	−210	2.57×10^4	−196	2.00×10^5
Oxygen	−219	1.39×10^4	−183	2.13×10^5



Source of both images: https://www.aplustopper.com/specific-latent-heat/ [Requested on February the 27th of 2022]

Based on that you can think about the total amount of heat that should be transferred to raise the temperature of 500 g water from -20 ºC to 110 ºC.

So, basically you will have 5 contributions that you will have to calculate one by one, before you add them.



Source: http://www.excelatphysics.com/heat-calculation.html [Requested on February the 27th of 2022]

- $Q_1 = m \cdot c_{ice} \cdot (T_f - T_0) = 500\, g \cdot (2,010\, J/g \cdot ºC) \cdot (0 - (-20))ºC = 20100\, J = 20,1\, KJ$
- $Q_2 = m \cdot L_f = 500\, g \cdot (336\, J/g) \cdot = 168000\, J = 168\, KJ$
- $Q_3 = m \cdot c_{water} \cdot (T_v - T_f) = 500\, g \cdot (4,184\, J/g \cdot ºC) \cdot (100 - 0)ºC = 209200\, J = 209,2\, KJ$
- $Q_4 = m \cdot L_v = 500\, g \cdot (226\, J/g) \cdot = 113000\, J = 113\, KJ$
- $Q_5 = m \cdot c_{steam} \cdot (T - T_v) = 500\, g \cdot (1,996\, J/g \cdot ºC) \cdot (110 - 100)ºC = 9980\, J = 9,98\, KJ$

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 = 520{,}28 \text{ KJ}$$

6.2.Dilatation.

When a body receives heat it increases the mean kinetic energy of their constituent particles (atoms, ions or molecules). As far as these particles move faster they tend to occupy more space. Despite that, because in solids and liquids attraction forces act between these particles[3], they can not move away from each other more than just a bit. Something different happens with a gas, which really expands when it gets heat because their particles are free, not bound at all to each other.

6.2.1. Dilatation in solids.

As you might know, the train rails are somewhat separated to prevent them from deforming when they expand in summer due to the increase in temperature. This is so due to the dilatation of solids, which is a phenomenon that only provokes a very small change in the volume by a given change in the temperature and it depends on each and every specific material by a coefficient called coefficient of linear dilatation.

[3] The attraction forces between particles in solids and liquids are related to intermolecular forces, such as hydrogen bonds, acting between the region of the molecules having a higher density of negative change and those having a higher density of positive change, as we will see in a deeper detail later on.

$$\frac{\Delta L}{L} = \alpha[\Delta T]$$

ΔL = Change in Length
ΔT = Change in Temperature
α = Coefficient of Thermal Expansion (CTE)

Coefficients of linear expansion

SUBSTANCE	α (per deg C)
aluminum	23×10^{-6}
brass	19×10^{-6}
glass	9×10^{-6}
rubber	80×10^{-6}
Ice	51×10^{-6}
lead	29×10^{-6}
steel	11×10^{-6}
concrete	10×10^{-6}

On the left, Author: Original uploader was Trainwatcher at English Wikipedia, Source: https://en.wikipedia.org/wiki/File:Rail_buckle.jpg
Center, Author: Daniel S. Sawyer (technical inquiries) and Jay Zimmerman (website); Source: https://emtoolbox.nist.gov/temperature/Slide2.asp
On the right, Source: https://slidetodoc.com/l-17-thermodynamics-2-science-dealing-with-the/ [All requested on March the 6th of 2022]

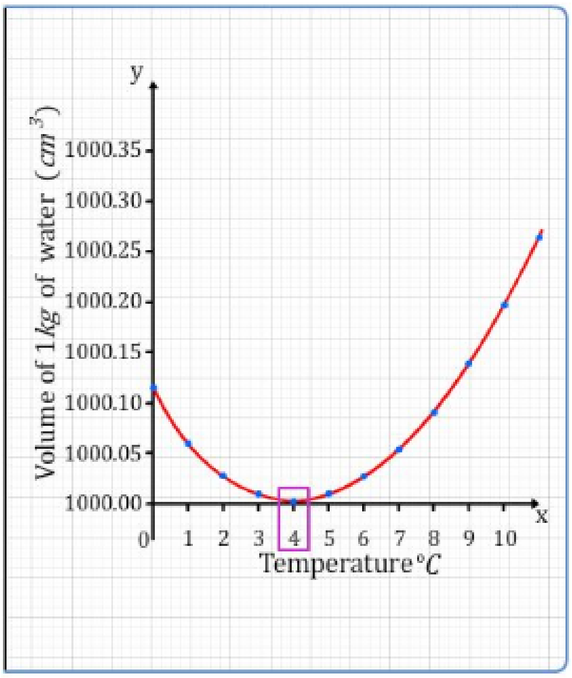
When the dilatation has to be calculated not as a change in length but as a change in surface or even volume, the corresponding surface or volume coefficient can be obtained by just multiplying the linear one by two or by three.

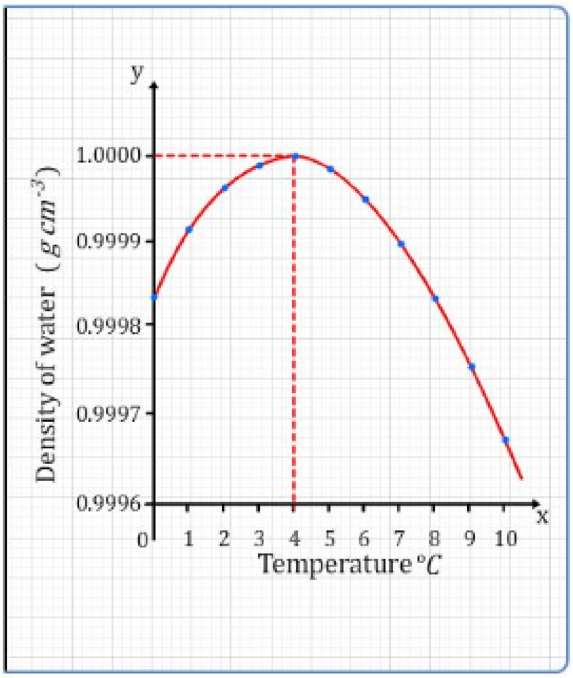
$S = S_0 + \sigma \cdot \Delta T$ $\quad V = V_0 + \gamma \cdot \Delta T$ $\quad \sigma = 2\alpha$ $\quad \gamma = 3\alpha$

6.2.2. Dilatation in liquids.

We can deal with dilatation in liquids the same way as we do for solids by using the same relationship for evaluating the change in volume just using other coefficients. Obviously these coefficients are higher for liquids than for solids, since dilatation in liquids is major than in solids, despite always being very small in comparison with a gas.

Here it is very interesting to highlight that, for water, this is a kind of excepcional behavior when the temperature is in the range between 0 and 4 ºC.

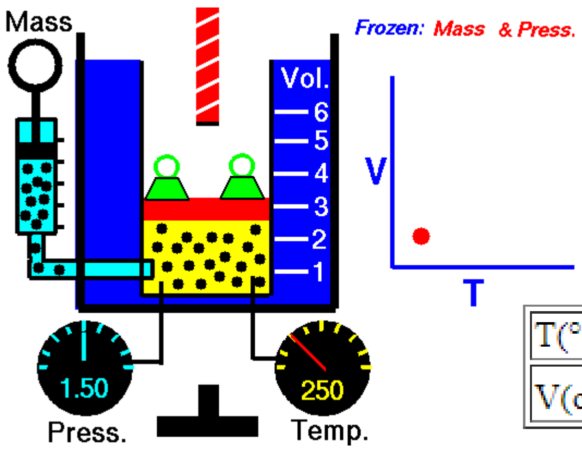




Source: https://www.toppr.com/ask/content/concept/anomalous-expansion-of-water-210020/ [Requested on March the 6th of 2022]

6.2.3. Dilatation in gas.

The relationship between volume and temperature of a gas was found by Charles (1797) and Guy-Lussac (1802) in an experimental way. Imagine you measure the volume of a gas and its temperatura when you heat it, obtaining the following values:

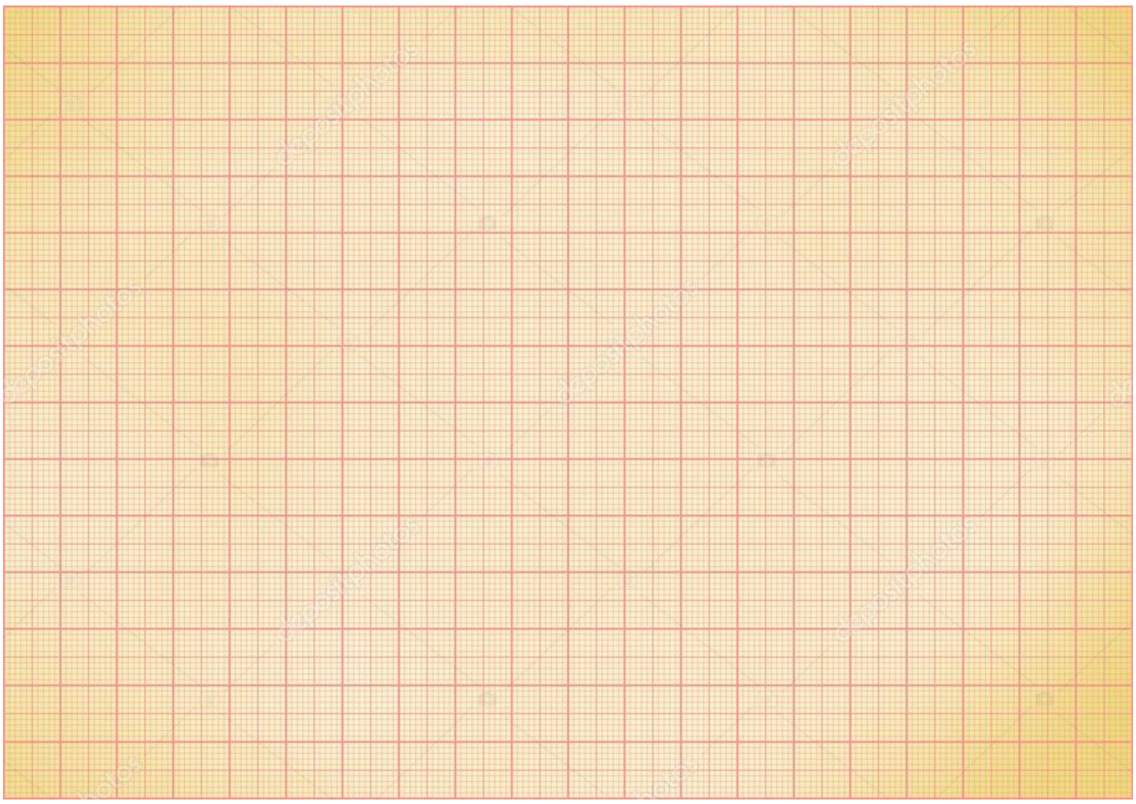


T(°C)	4.8	17.1	28.4	41.6	54.8	65.1	75.4	87.1	96.9
V(cm^3)	44.0	46.0	48.0	50.0	52.5	54.0	56.0	56.5	57.5

Author: public domain image from Pfctdayelise Source: https://commons.wikimedia.org/wiki/File:Charles_and_Gay-Lussac%27s_Law_animated.gif
Source: http://www.fed.cuhk.edu.hk/~physics/exp_charles_law_e.html [Both requested on March the 6th of 2022]

Represents the previous measurements on the piece of millimeter sheet:

- placing the temperature in ºC on the horizontal axis on the first main line starting at the bottom, using an integer grid for each 20 ºC interval and
- placing the volume in cm^3 on the vertical axis, we will draw 5 grids from the right margin, using two whole grids for each cubic centimeter (cm^3).



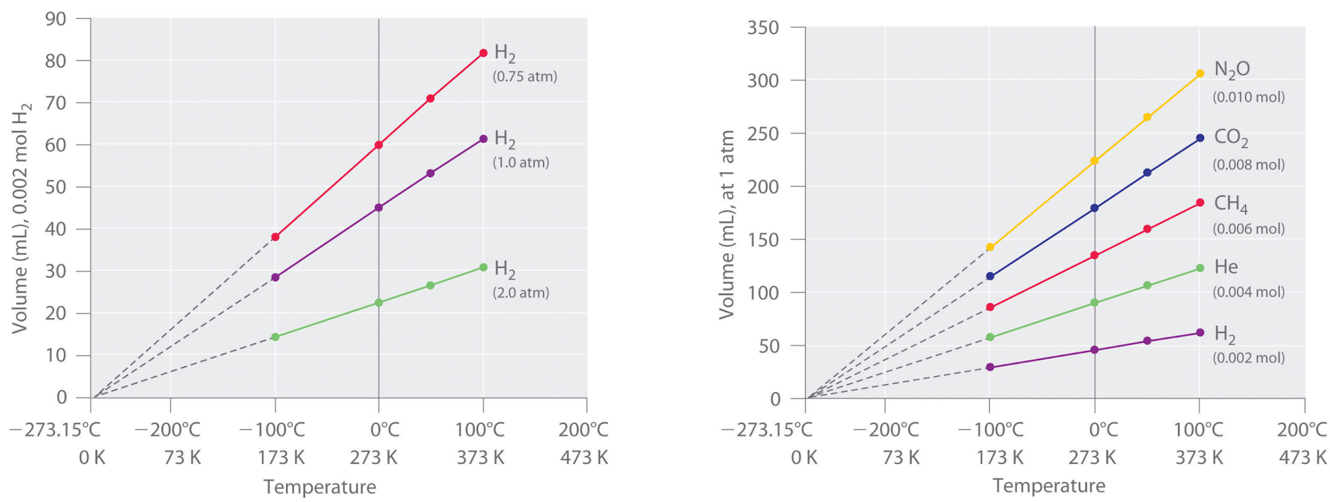
QUESTION: Determine graphically the value of the temperature by which the volume would be reduced to 0.

6.2.3.1. Absolut origin of temperatures.

If we repeat the previous experiment for:

- he same gas, keeping the pressure constant but in several values or
- for different gases…

WE WILL ALWAYS GET THE SAME VALUE FOR THE MINIMUM TEMPERATURE THAT WOULD CORRESPOND TO A VOLUME V = 0 L!!!



(a) (b)

Source: https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_Chemistry_(Zumdahl_and_Decoste)/05%3A_Gases/5.02_The_Gas_Laws_of_Boyle_Charles_and_Avogadro l [Both requested on March the 6th of 2022]

THIS IS THE ABSOLUTE ORIGIN OF TEMPERATURES, BELOW WHICH IT IS IMPOSSIBLE TO LOWER and THE ORIGIN OF THE KELVIN SCALE INTRODUCED IN SECTION 4.