Temperature Measurements

Basics

I'm sure you know the difference between hot and cold water. If not, stir your iced drink and your boiling soup a while with your finger and you shall know. You probably also know the difference between a cold piece of iron an a hot one. If not, just touch the exhaust pipe of your car after you went for a long ride.

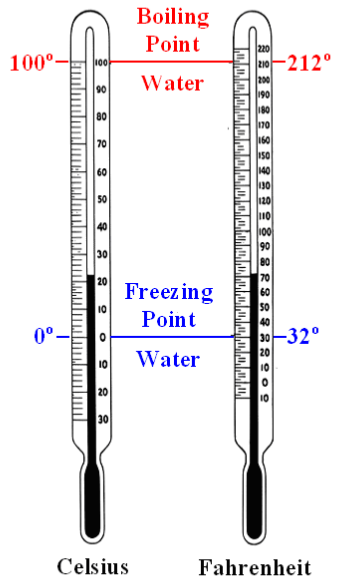
- It's easy to know if an inanimate object is hot or cold. You find out by touching it. With animated objects it might be more difficult. How hot is that lady over there? Finding out by touching might not be such a good idea.
- How about *measuring* "hotness" or "coldness"? That means to put a number on coldness and hotness and call it *temperature*.
  Typically you must now touch the object with some device that gives you a response on some *scale*.
  You now have two problems:

  1. What kind of *device* could do that?
  2. What kind of *scale* should I choose?

  Despite appearances, the two problems are completely unconnected. That becomes clear immediately if you look at the simplest device for measuring temperature: the good old mercury (Hg) thermometer. Mercury (or other liquids like alcohol) expand when becoming hot, and the top of a column of the stuff contained in a thin glass capillary will climb up if the temperature goes up.
- OK, we solved the *first problem*. We now have some device that responds to temperature by moving a "pointer" (the top of the column) up and down a scale.
  But what kind of number do I put on the *scale* next to the capillary? Is there some universal principle that I can use for guidance?
  Yes there is. For questions like this, the universal principle is:

Ask your friendly Materials Scientist

- In this case she will weasel a bit. She might mumble that the best way would be to express temperature in terms of *energy*, but that you won't get this, and that the next best thing would be to use the so-called *absolute temperature scale*, which gives temperatures in "Kelvin (K)". It's just Kelvin, not "degree Kelvin"; no ~~^{o}K~~.
  However, if you press her a bit, she will admit that in everyday life she actually uses centigrades (^{o}C), degree Fahrenheits (^{o}F) or whatever else she grew up with (if she is of French origin it might be Réaumur (^{o}R) but we won't hold that against her).

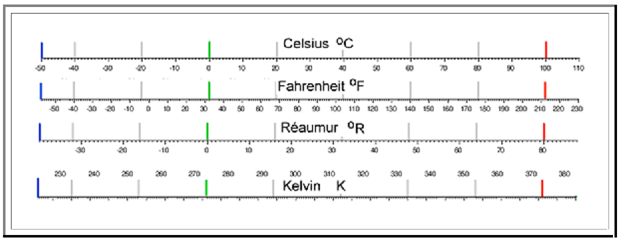


Temperature measuring devices called thermometers

  - Both thermometers measure the same *thing* ("temperature") but with different *scales*: degree Celsius or degree Fahrenheit.

- The guys who invented the first thermometers (there were only guys, female scientists hadn't been invented or discovered yet) had different ideas about how to fix a scale.
  - The Swedish astronomer **Anders Celsius** in 1742 assigned 0 °C to the *freezing* point of water and 100 °C to the *boiling* point. In between the scale was subdivided in 100 parts (defining a temperature difference of **1 °C**), which allows to extrapolate to temperatures above 100 °C and below 0 °C. 1)
    The Celsius scale is the scale almost everybody uses today (even the French).
  - **Daniel Gabriel Fahrenheit**, a German from Danzig, begged to differ in 1714. He picked as the zero point (0 °F) of his scale the low temperature of the stiff winter 1708/1709 in Danzig (-17,8 °C on the Celsius scale), because he wanted to avoid negative numbers. For rather obscure reasons 2) he took 32 °F for the freezing point of water, which automatically leads to 96 °F as another fixed point for the body temperature of humans.
    From a scientific point of view the Fahrenheit scale is problematic because its fixed points are not well defined. From a practical point of view it is a great scale because 0 °F - 100 °F defines about the extremes of temperature humans may experience. You know that 0 °F is lousily cold and 100 °F is scaldingly hot.
    Fahrenheit is still the official scale of the United States, Thailand and Belize; in Canada it is retained as a secondary scale. The rest of humankind uses °C or "**centigrades**".
  - **René Antoine Ferchault de Réaumur** proposed a scale with 0 °R as the freezing point of water and 80 °R for the boiling point. Why 80 and not 100 or 72,6 or whatever was a kind of mystery until I found the explanation. 3)
    My own explanation was that the French have trouble counting beyond 20, and going up to 100 was just too challenging. 80, in French is "quatre vingt", i.e. 4 times 20; 90 is "quatre-vingt-dix", i.e. 4 times 20 and 10. Counting just gets too complicated above eighty.
  - There are several other scales, all but forgotten, and I won't go into this anymore.

- Instead we give a look at the scientifically important **Kelvin scale** or **absolute temperature scale**. It rests on the tremendous insight that there is a lowest temperature, a coldness that cannot be surpassed, a natural **absolute zero point of temperature**. You can't do better than that to define 0 K or **zero Kelvin**.
  - Going up is done with intervals borrowed from the Celsius scale. A difference of 10 K is the same *difference* between some two temperatures as 10 °C difference.
    There is no particular reason for using Celsius, except that it was convenient for the majority of scientists who were used to the Celsius scale by their upbringing.
  - The Kelvin scale is so important in science because **absolute temperature** measured in Kelvin (and then always abbreviated ***T***) can go right into equations and formulae.
  - Here is a conversion diagram for the four scales discussed:



- I must now discuss all those questions that accumulated in the back of your mind. Let's bring them out:

  1. How do we measure temperatures *outside* the range of common thermometers? If it's too cold, the liquids in the capillary will freeze; if it's too hot, they evaporate or the capillary melts. When we forge iron and steel it needs to be pretty hot and you have never seen a smith sticking a thermometer into his hearth.
  2. Why does mercury (Hg) or just about everything *expand* more or less when it gets hotter?
  3. What *is* temperature, anyway? After all, if you look closely—very closely— at a piece of hot or cold water, you "see" those little things, whatchamacallit?", those *water* **molecules** (H_2O). There is a certain (large) number in a liter of water, and heating or cooling does *not* change that number nor the molecules. Same thing for hot or cold steel, except that instead of molecules you now see mostly iron **atoms**. Same thing for simply *anything*. The questions thus is: what's the difference between the hot or cold molecules or atoms that form the material you are contemplating?

  I bet you weren't quite aware that those questions were at the back of your mind. Now you are—and I must answer them.

- 1. How do we measure (**extreme**) temperatures? There are many ways; we will only give some of them a quick glance.

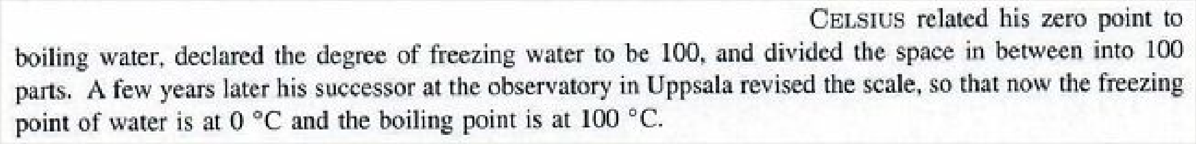
  - Most simple and wide spread is the use of a *resistor* that changes its electrical resistivity in a well defined way with temperature. Platinum (in a thin layer, so you only need tiny amounts) does just that. And no, I won't go into why Pt (and just about everything else) changes its resistivity with temperature.
    That's great because this allows you to generate an *electrical signal*, that can be processed directly by the "electronics inside" that run about everything today. Platinum is also a great material for this because it will not corrode and can take high temperatures because its melting point is 1.772 °C (3.222 °F)
  - Quite simple and widespread are also "**thermocouples**", a junction between two different materials. If that junction is at a temperature different from that of the rest of the material, a voltage develops that is indicative of the temperature (difference) and that you can easily measure with a voltmeter. An no, once more, I will not even try to attempt to explain why that happens.
    Thermocouples are widely used at high temperatures and when precision counts.
  - What are we going to do at *really* high temperatures, when pretty much everything would be molten? Easy. We look at the *light* emanating from *all* hot bodies.
    What you and just about everybody else knows is that hot things start to glow. Increasing the temperature of a piece of steel changes its color from dark red, via cherry red, orange, yellow to white (and eventually blue if it wouldn't melt before that happens).
    So by measuring *precisely* what kind of color (more precisely: spectrum) a hot piece of iron assumes, we can compute it's temperature.
    What you probably don't know is that the composition of the light (the spectrum) that hot bodies emit is the *same* for all hot bodies. This includes *your* hot body, the sun, everything. If I would heat you up to 1.000 °C (1.832 °F), you would glow *exactly* like a piece of iron or whatever. I admit that heating you up that much in air would induce some changes in your body (described as "burning" or "oxidation") that are not enjoyable as we know from many experiments performed by the church a few hundred years ago. So we heat you up in an oxygen-free environment (not enjoyable either) and glow you will.

- It was **Max Planck** in 1900 who discovered the universal law of "black body" radiation (no, he wasn't thinking of your body after the experiment described above). His famous equations not only fits the observations very well and and allows us to measure temperature by just "looking" at an object with a spectrometer, it opened the door to **quantum theory**.
  - In fact, the glowing of hot objects in "colors" that betray their temperature can *only* be understood by quantum theory. We have a first little indication here that quantum theory is not just something physicists amuse themselves with when dealing with exotic things that have nothing to do with everyday life. Just the opposite. Whenever a smith looks at his hot piece of steel to judge by its color if its temperature is right, he is doing quantum theory, probably without knowing that.

- We have two questions left. But I stop here. After all, this is a "BASIC" module.
  - I will, however, take up those questions at some other parts of the hyperscript. If you make it that far, you will learn that knowing the answer to question three is absolutely essential for understanding how to make good swords.

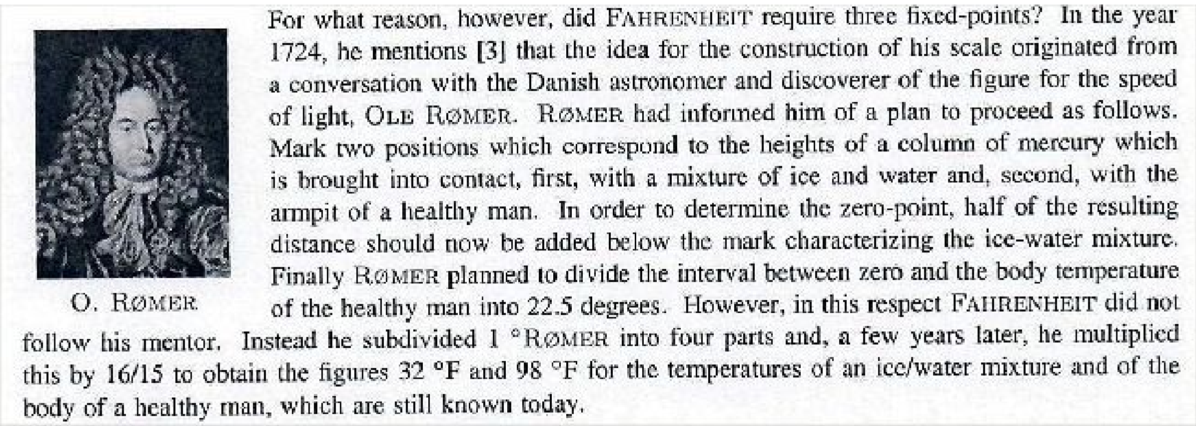
The following footnotes come all from this article: W. Dreyer, W.H. Müller and W. Weiss: "Tales of Thermodynamics and Obscure Applications of the Second Law", Continuum Mechanics, Thermodyn. **12** (2000) pp 151 - 184

1)



CELSIUS related his zero point to boiling water, declared the degree of freezing water to be 100, and divided the space in between into 100 parts. A few years later his successor at the observatory in Uppsala revised the scale, so that now the freezing point of water is at 0 °C and the boiling point is at 100 °C.

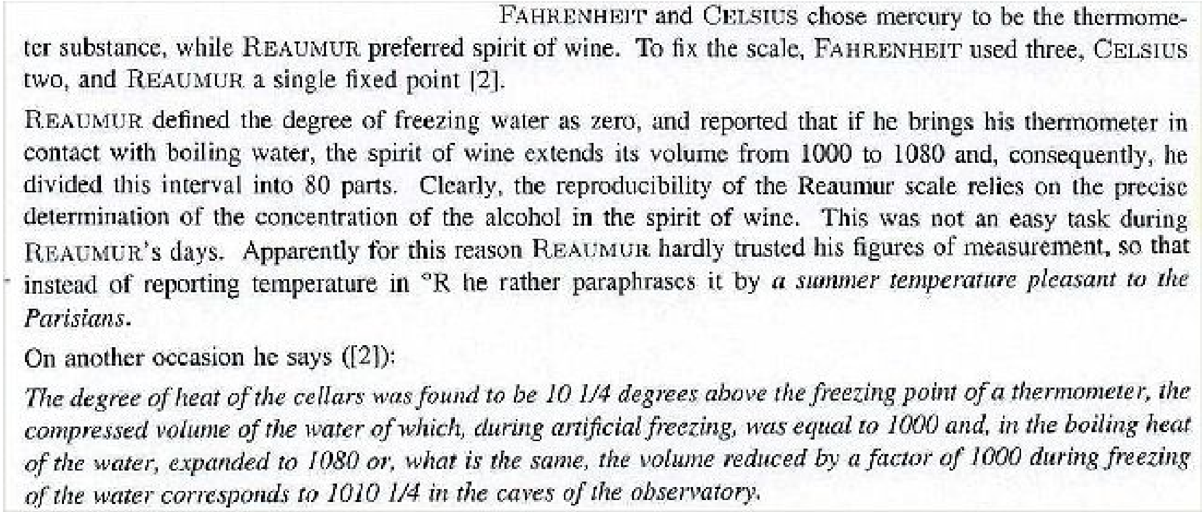
2)



O. RØMER

For what reason, however, did FAHRENHEIT require three fixed-points? In the year 1724, he mentions [3] that the idea for the construction of his scale originated from a conversation with the Danish astronomer and discoverer of the figure for the speed of light, OLE RØMER. RØMER had informed him of a plan to proceed as follows. Mark two positions which correspond to the heights of a column of mercury which is brought into contact, first, with a mixture of ice and water and, second, with the armpit of a healthy man. In order to determine the zero-point, half of the resulting distance should now be added below the mark characterizing the ice-water mixture. Finally RØMER planned to divide the interval between zero and the body temperature of the healthy man into 22.5 degrees. However, in this respect FAHRENHEIT did not follow his mentor. Instead he subdivided 1 °RØMER into four parts and, a few years later, he multiplied this by 16/15 to obtain the figures 32 °F and 98 °F for the temperatures of an ice/water mixture and of the body of a healthy man, which are still known today.

3)



FAHRENHEIT and CELSIUS chose mercury to be the thermometer substance, while REAUMUR preferred spirit of wine. To fix the scale, FAHRENHEIT used three, CELSIUS two, and REAUMUR a single fixed point [2].

REAUMUR defined the degree of freezing water as zero, and reported that if he brings his thermometer in contact with boiling water, the spirit of wine extends its volume from 1000 to 1080 and, consequently, he divided this interval into 80 parts. Clearly, the reproducibility of the Reaumur scale relies on the precise determination of the concentration of the alcohol in the spirit of wine. This was not an easy task during REAUMUR's days. Apparently for this reason REAUMUR hardly trusted his figures of measurement, so that instead of reporting temperature in °R he rather paraphrases it by *a summer temperature pleasant to the Parisians*.

On another occasion he says ([2]):

The degree of heat of the cellars was found to be 10 1/4 degrees above the freezing point of a thermometer, the compressed volume of the water of which, during artificial freezing, was equal to 1000 and, in the boiling heat of the water, expanded to 1080 or, what is the same, the volume reduced by a factor of 1000 during freezing of the water corresponds to 1010 1/4 in the caves of the observatory.