Why does water boil at 212°F?

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At a recent professional development course, I was asked: Why is the boiling point of water 212 °F? What was the origin of the choice of this fixed point? This note is intended (1) to provide a brief history of the reasons for the choice of the fixed points, and (2) to suggest some ways interesting information about temperature can be used in the classroom. It’s worth revising briefly first some key ideas about thermodynamics.

Background

Heat and temperature

In everyday language, we describe something as ‘hot’ or ‘cold’. This physiological sensation can be quite misleading: two objects, such as a glass container and a metal container, can be at the same temperature, but the metal may seem ‘colder’. Physicians were familiar with the idea of a temperature scale long before there was an instrument to measure it (Knowles Middleton, 1966).

Temperature is quite different from many other units we use in science. For example, unlike mass and length, temperature is not additive: two liquids, one at 30°C and the other at 40°C will not result in a liquid with a temperature of 70°C when mixed. Further, temperature is not a property of a specific piece of material: eventually, different materials will come to the same temperature in a closed system.

What is temperature? According to Chambers Science and Technology Dictionary (1991) temperature is “a measure of whether two systems are relatively hot or cold with respect to each other” (p. 889) and heat is “the process of transfer between a system and its surroundings as a result of temperature differences” (p. 420). The measurement of temperature depends on the “zero law” of thermodynamics.

Laws of thermodynamics

The four laws of thermodynamics were developed during the nineteenth and early twentieth centuries. The ‘zero law’ was formulated after the first law had been well established. The New York Public Library’s (1995) Science reference desk formulates laws of thermodynamics this way:

0. No heat flows between any two bodies that are at the same temperature.

1. In narrow terms, the first law of thermodynamics states that the energy used in doing work will be equal to the amount of work done, plus the heat lost in the process. ...

2. Heat will always flow “downhill”, i.e., from an object having a higher temperature to one having a lower temperature; thus it is impossible for heat to flow spontaneously from an object with lower temperature to one with a higher temperature, and work must be done to transfer heat energy from a lower temperature to a high temperature.

3. A temperature of absolute zero - believed to be the lowest possible temperature in the universe - is the point at which all molecular motion ceases.

These laws in effect tell us that you can’t get more energy out of a system than goes in. Some scientists have paraphrased laws 1-3 in this way:

1. You can’t win.

2. You can’t break even.

3. You can’t get out of the game.

Brief history of fixed points

The measurement of temperature relies on some physical property, such as volume or electrical resistance, changing reproducibly as the temperature rises. These changes must occur in different localities for standards to be developed. Change in volume has been chosen as the common indication of temperature change for historical reasons. However, two further choices need to be made: the thermometric substance and the numbering of the scale (Knowles Middleton, 1966).

The first thermometric substance used was air, presumably because its volume changed satisfyingly with temperature. However, in the 1640s the recognition of the variance in atmospheric pressure led to an interest in liquids. Mercury was not considered suitable because its change in volume was small as the temperature rose.

It’s important to remember that when Daniel Fahrenheit developed his scale, there was no standard thermometric scale which allowed scientists to compare temperature. In fact, there were no thermometers as we know them today.

Galileo was thought to have invented the air thermometer in about 1592. However, despite the use of this thermometer, no attempt appears to have been made to develop a scale. The first ‘real’ thermometer was probably devised by Ferdinand II, Grand Duke of Tuscany, in 1641. This was a sealed alcohol-in-glass thermometer. The stems of these thermometers were marked by equal intervals of fractions of the volume of the bulb. The glass blowers of Northern Italy used their skills to produce many fanciful thermometers. Members of the Academia del Cimento experimented with mercury instead of alcohol, but concluded that mercury was less suitable than alcohol.

Thus, while sensitive thermometers were now available, there was the lack of a universal temperature scale. Remember that there was a complete ignorance of the idea of fixed points. Further, there was little appreciation of the depen-
ence of the scale on the liquid used in the thermometer.

According to the Dictionary of Scientific Biography (1971), Daniel Fahrenheit was the “scion of a wealthy merchant family.” His parents died in 1701, and he was sent to Amsterdam to learn business. There he became fascinated with scientific instrument making, including thermometers.

Olaus Roemer, the Danish astronomer, developed a spirit thermometer with two fixed points. One was the boiling point of water, fixed at 60°. The second was the temperature of melting ice, set at 7.5°. Over this scale, the temperature of an ice/salt mixture (considered to be the lowest possible temperature) was 0°.

Fahrenheit watched Roemer, in 1708, graduate some of his thermometers. One of the fixed points was ‘blood warm’ which could mean either a tepid temperature or the temperature of warm blood. Roemer probably meant the first interpretation and Fahrenheit the second.

The upper fixed point in Fahrenheit’s scale initially corresponded to the temperature of a healthy male and the lower point to the temperature of an ice/water mixture. The upper point was labelled 90°, the lower one 30°. These were later changed to 96 and 32 to remove the ‘awkward fraction’. On this scale, water boiled at 212°, presumably by extrapolation beyond the 96 point; Fahrenheit did not fix 212 as the upper fixed point. Remember, though, that normal body temperature is about 98.6°F, so the value of 212 was likely wrong; in fact thermometers used by some others gave a value of 214°. By about 1740, thermometers routinely used in Britain and Holland had 212° as the boiling point of water and the upper fixed point.

Classroom investigations

Ideas about heat and temperature can form the basis of some interesting classroom investigations, from ‘What is normal body temperature?’ to ‘How do we measure the temperature of stars?’ Below are some ideas which are linked to the five key areas of the science curriculum.

Working scientifically

The history of the development of the laboratory thermometer provides a wealth of data about science, and in particular how science and technology have interacted over time. Some of the references below will provide starting points for investigations. The thermometer is one of the most commonly used pieces of equipment in the laboratory, and perhaps the most taken-for-granted.

Life and living: What is the ‘normal’ temperature of the human body?

I’ve always assumed it was 98.6°F or 37.0°C. Why? Because every textbook I’ve read tells me so. When I read Paulos’ (1995) claim that average body temperature is 98.2°F, not 98.6°F, and that the latter value is the result of rounding from 37°C, I was surprised. The following website suggests Paulos’ claim may be true: [http://www.columbia.edu/~gae4/facts/LenaWong.html]

The following website, by Shoemaker, also gives a value of 98.2°F: [http://jse.stat.ncsu.edu/70/0/jse/v4n2/datasets. shoemaker]. He wrote:

The data were derived from an article in the Journal of the American Medical Association … The authors display a histogram of 148 subjects’ normal temperatures taken at several different times during two consecutive days, resulting in 700 total readings.

He provides data which he uses to illustrate some procedures in statistical analysis. You might like to try some of these activities, perhaps in conjunction with the mathematics staff.

Energy and change: Thermometers and thermodynamics

Basic information about thermometers is provided in: [http://www.meteo.niu.edu/explore/thermometer.html]. There are different thermometers for different purposes. Key ideas about energy and energy change were important in developing technologies in thermometer construction. Which would you expect to freeze more quickly, a warm sample of water or a cooler sample of water, if they are both cooled rapidly at the same rate? The answer is surprising: see M. Berthelot and Osborne (1969) and Walker (1977).

Earth and beyond: Is there any uppermost temperature?

As far as we know there is no upper limit to temperature. This website provides some background on this: [http://windows.engin.umich.edu/kids_space/star_temp.html]. One important question is, of course, how do we measure these high temperatures? Ordinary thermometers clearly are not the answer. In fact, spectroscopy is used to measure high temperatures such as those in a rocket engine: [http://www. giss.nasa.gov/research/intro/green/02/]

Students might like to investigate how sound is used to take the sea’s temperature: [http://www.sciencenews.org/ sn_arc98/8_29_98/feb4Ref.htm]

Natural and processed materials: What makes a material useful in a thermometer?

The common laboratory thermometer uses a liquid: either mercury or ethanol. Solids are used in the oven thermometer, usually as a bimetallic strip which distorts as temperature increases or decreases. Most recently, liquid crystals have been used. Bloomfield (1997) describes the use of chiral nematic liquid crystal in ‘strip thermometers’; these are small strips in which the number corresponding to a particular temperature becomes visible.

More classroom investigations

More classroom investigations can be based around some interesting temperature related facts. Below is a
collection interesting information gathered from the sources listed in the references.

- People have walked across coals heated to 841°C.
- Saunas at 140°C can be enjoyed comfortably.
- Mercury thermometers would freeze at -39°C.
- Earth’s highest recorded temperature in the shade is 58°C.
- Lowest recorded surface temperature is -89.2°C.
- Some bacteria survive 70°C.
- Temperature of arctic sea water is -1.1°C.
- Gold boils at 2900°C.
- Surface temperature of the sun is 5330°C.
- The lowest temperature recorded in the northern hemisphere is -71°C in the village of Oymyakon in eastern Siberia.
- Africa, the warmest of the continents, has thirteen square kilometres of glaciers on three of its highest mountain peaks. Only Australia, of all the continents, has no glaciers, because there are few mountains.
- The temperature can be so low in eastern Siberia that the moisture in a person's breath can freeze in the air and fall to the earth with soft crackling or whisper sounds.
- The temperature of boiling water depends on where you are. The temperature, in °C, at various places is: Dead Sea, 101; London, 100; Quito, Ecuador, 90; Mt Everest (top), 71.
- The common mercury-in-glass thermometer is not much use in cold climates where the temperature dips below -39°C (the freezing point of mercury). What about ethanol? It freezes at -114°C.

Finally ...

While I researched this topic, I was on study leave at Cornell University. I came across a speech by Albert Johnson to the US House of Representatives on December 14, 1915. He proposed a Bill to abolish the Fahrenheit scale in US government publications. Attached to his speech were many letters he received in support of his bill. Among the many replies, here is a brief extract:

While I am duly conscious of the criminal waste of time which has been imposed upon the people of this country by the Fahrenheit scale, still I am disposed to exercise clemency, and would suggest the thermometer be not abolished, but simply retired to the privacy of museums, there to remain as evidence of foolish and wasteful conservatism. (Robert H Wolcott, cited in Johnson, 1916).

References

