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Evolution of temperature measurement – beginnings, progress and prospects

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Evolution of temperature measurement – beginnings, progress and prospects

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Abstract. This paper starts by charting the development of temperature measurement from its beginnings with the thermoscope in the late 1500s through to liquid-in-glass and air thermometers in the 1600s and 1700s. The emergence of classical thermodynamics which put thermometry onto a sound physical footing is then briefly described as is the convergence of practical and thermodynamic thermometry in the late 1880s and early 1900s through the use of defined scales, which became the benchmark for reliable thermometry throughout the 20th century and beyond. Finally an outline of the kelvin redefinition in 2019 and its implications is given followed by a discussion of the prospect of driftless practical primary thermometry across a wide temperature range by the 2050s.

1. Introduction

Temperature has a crucial role to play regarding living things. Life as we know it can only exist in a narrow range of temperatures; too hot or too cold and life would be impossible. For example, our near neighbour planet Venus, so long thought to be like the Earth, is in fact far too hot for life to exist with runaway greenhouse effects meaning the surface temperatures are higher than the melting point of lead (about 327 ºC). On the other hand Mars, so often seen as a reservoir of hostile aliens poised to invade the Earth, is in fact far too cold to sustain intelligent life, the average surface temperature being around -60 ºC. The Earth meanwhile sits in that narrow zone in the Solar System at a temperature which sustains plentiful liquid water on which all life depends. Besides that temperature affects so many aspects of life, being a key driver of thermochemical processes at the cellular level, essential for seed germination and crop yields, and a key indicator of human health, necessary for reliable meteorology and monitoring climate change and so much more. Indeed at the present time reliable temperature measurement is so ubiquitous, so common place, that no one gives it a second thought. And yet for much of history the measurement of temperature was not possible, and only the unreliable comparative sensations of "hot" and "cold" were known. Indeed it was only in recent times that meaningful temperature measurement was performed and certainly it was only within the last two hundred years that any real understanding of temperature emerged.

This paper charts the emergence of reliable temperature measurement beginning in the late 16th century with the thermoscope, leading to the emergence of true thermometers by the early to mid-1600s. A bewildering array of different temperature scales were developed and used in the 18th century, but these had reduced to three main scales by the mid-1800s. Then with the work of Thomson (Lord Kelvin) and Joule the scientific discipline of classical thermodynamics emerged, definitively establishing the intimate connection between temperature and energy. A little later through the work of James Clerk Maxwell and Ludwig Boltzmann, the discipline of statistical thermodynamics was founded and the

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physical background to temperature at the atomic level was truly understood. The work, especially of Thomson and Joule, led to physically-based temperature measurement using gas thermometry. With the emergence of defined temperature scales, founded on primary thermometry measurements but realised using practical thermometers such as those based on the resistance of platinum, reliable thermometry was established on a global footing in the 20th century. Finally with the redefinition of the kelvin in 2019 a new "golden age" of primary thermometry has emerged where it is anticipated that future practical temperature measurement will be directly linked to the kelvin definition and no longer mediated by a defined scale. The paper will end with suggestions as to how thermometry could evolve into the mid-21st century.

2. Beginnings of temperature measurement

This section will describe the beginnings of thermometry with the (re)invention of the thermoscope, the invention of true thermometers, and the explosion in the number and diversity of temperature scales and the fixed points used to establish them.

2.1. The thermoscope

Although the familiar terms of "hot" and "cold" were commonly used for millennia, an objective way of measuring temperature only emerged during the early scientific explorations in the Renaissance period. The starting point was the re-invention of the thermoscope, most famously by Galileo Galilei in the 1590s. Re-invention is stated because its principle was known in antiquity, being described in writings by Hero of Alexandria and Philo of Byzantium; and indeed it may have been through reading their works that Galileo was inspired to make his investigations [1].

A photograph of a thermoscope is shown in figure 1. It is a simple device consisting of a lower vessel containing water, an upper vessel (bulb) containing air and a thin glass tube, containing a column of water, connecting the two. The principle of a thermoscope is straightforward: if the upper bulb is warmed the temperature increases as does the air pressure forcing the water down the connecting glass tube into the lower vessel. The opposite is the case if temperature decreases; the air pressure in the upper vessel decreases and the water ascends the connecting glass tube. This direction the liquid moves in is opposite to modern thermometers and may have had an influence on the scales of some early thermometers whose scales decreased in numerical value as temperatures increased (see for example figure 3).

Figure 1. Photograph of a thermoscope – courtesy of Museo Galileo Istituto e Museo di Storia della Scienza, Firenze.

2.2. Emergence of thermometers

The thermoscope was not a thermometer since the latter requires an objective way of indicating the measured temperature, not just relying on qualitative changes. This was recognised by a number of people, not only by Galileo but also others. By the early 1600s thermometers based on the principle of a thermoscope but with a scale added were being made. For instance, the following remark is found by Santorio Santorre (Sanctorius), Professor of Medicine at Padua and a contemporary of Galileo, about how he developed a scale for his thermoscope using two "fixed points", *"..apply snow to the sphere of the glass instrument so that the water may ascend to its upper limit. Then with the flame of a candle we can make the water descend as far as it will go…*" [2]. Here there are the rudiments of a thermometer described – something that senses the change of temperature (the water moving in the column) and a way of *establishing a scale* to objectively record the indicated changes (in this case two "fixed" points [although of course neither snow nor a flame are true fixed points – but that is only known with hindsight]).

The water-based thermoscope had a number of serious flaws with regard to being a thermometer. Firstly, water is a poor liquid to use since it does not have a linear expansivity with temperature (e.g. it has a maximum density at 4 ºC). Secondly, it also freezes at 0 ºC and so could not cover a very wide range of temperatures. Thirdly, the thermoscope is open to air and so variations in air pressure also affected the level of liquid in the tube.

These flaws were recognised quite soon after the thermoscope-based thermometer was introduced, but all these were overcome through the innovation in 1654 by Ferdinando II d'Medici, Grand Duke of Tuscany. He used as thermometers sealed glass tubes part-filled with alcohol. This rapidly led to the development of elaborate, beautiful even, glass thermometers, exquisitely sensitive and uniform in construction thanks to the great skill of Florentine glass blowers. An example of such a thermometer is shown in figure 2. This thermometer has four hundred and twenty enamel scale markers calibrated at the fixed points of snow and the "hottest day in Florence" (note again that these are not true fixed points).

Figure 2. Photograph of spiral thermometer, the scale indicated by blue enamel markers, – courtesy of Museo Galileo Istituto e Museo di Storia della Scienza, Firenze.

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In the following years the basic design of the thermometer remained unchanged, i.e. it is a sealed glass tube with a bulb at the lower end that contained a liquid sensitive to temperature. In the early days of thermometry the liquid was mainly alcohol, but increasingly over time the liquid metal mercury was used, being more linear in its expansivity and having a wider temperature range of application.

2.3. Temperature scales and fixed points

In the absence of any form of standardisation there was an explosion in the variety of scales which were attached to the thermometers. This was in part due to the fact that there was no general agreement as to what fixed points to use or even what was a fixed point (for example, there was "hot" debate about whether the boiling point of water was a fixed temperature [which it is *if* the pressure is standardised]) and in part due to the fact that the underlying physics of temperature was not understood (that would have to wait until the 1850s and later). So a wide variety of fixed points used for calibrating thermometers was found. Some would be considered usual, such as melting ice and boiling water or even the human body temperature, whilst others, to our modern thinking at least, are quite bizarre, for example the melting point of butter or the temperature of a very deep cellar under the Paris Observatory [3]. Examples of the effect of the diversity of the fixed points used can be seen in figures 3 and 4. In figure 3 a photograph of a thermometer with an early "Royal Society" scale is shown. Note that it is an inverted scale with "very hot" being at 5 degrees and freezing being at 65 degrees. In figure 4 there is a photograph of a thermometer from the University Museum, Utrecht with eighteen of the temperature scales that were in use at the time so that the user of a particular thermometer could convert from one scale to another.

This situation could not continue and whilst there were no real concerted efforts by the scientific community to reduce the number of scales, and hence achieve more regularised temperature measurement, eventually three temperature scales won out. Thus, by the first half of the 18th century there were mainly three in use, the Fahrenheit, the Réaumur and the Centigrade.

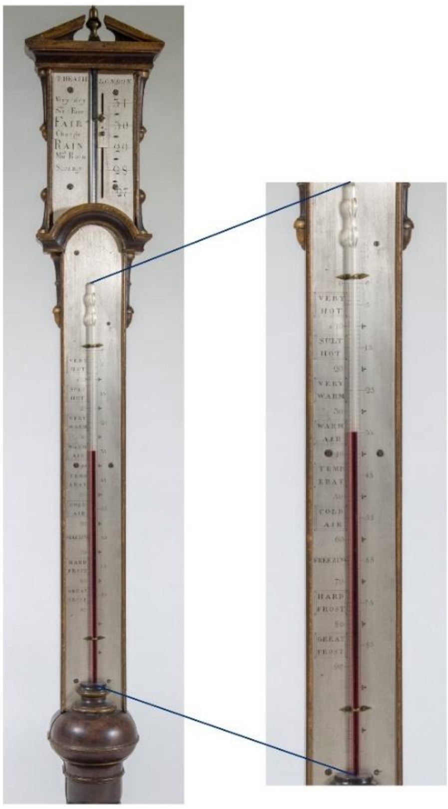

Figure 3. Royal Society Thermometer with inverted scale c. 1720s. Courtesy of the Museum of the History of Science, University of Oxford.

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2.3.1. The Fahrenheit scale.

Daniel Fahrenheit (1686–1736) was born in Danzig but lived mainly in The Netherlands and worked as an instrument maker. He used mercury as his thermometric liquid. His scale (he claimed) had three fixed points: human body temperature (which he defined as 96^0), an intermediate point (a mixture of ice and water) at 32^0 and a lower point which he obscurely defined as the temperature of a solution of brine made from equal parts of ice, water and salt (sea-salt or ammonium chloride) defined as 0^0 [4]. However, it is unlikely that the lower point was in any way reliable and in reality only the first two points were usable fixed points.

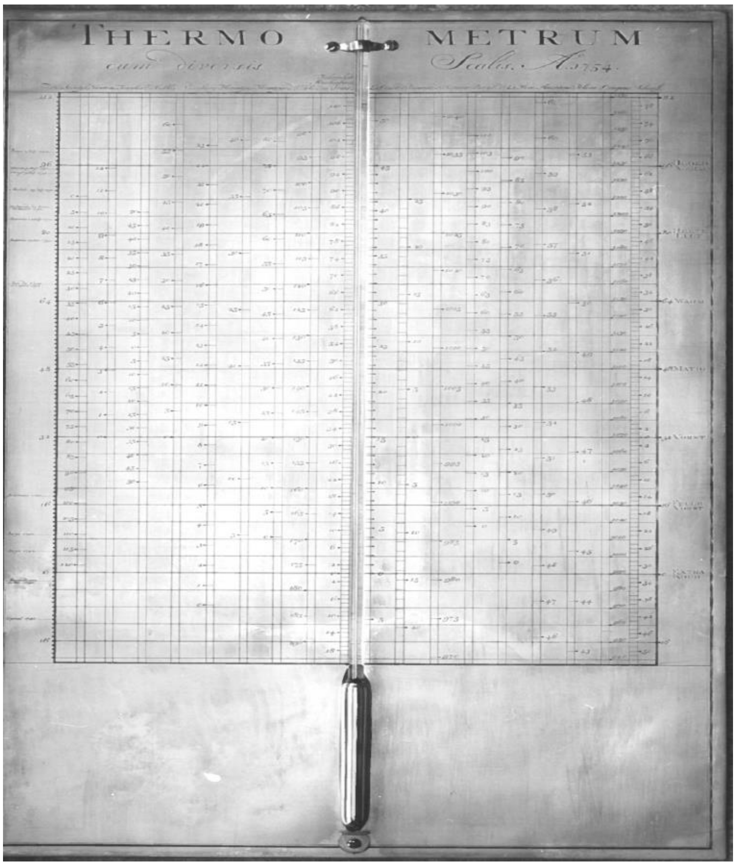

Figure 4. Thermometer with 18 scales (1754) Courtesy of University Museum Utrecht, inv.nr W-11.

2.3.2. The Réaumur scale.

René-Antoine Réaumur (1683–1757) was a renowned French scientist, a member of the Academie des Sciences, who contributed to many scientific fields. His original thermometers used alcohol “spirit of wine” as the thermometric liquid. He proposed a scale in c. 1731, the lower fixed point being the freezing point of water at 0 ^{0}Ré. The upper fixed point description was very confused, but most people believed that he was saying that 80 ^{0}Ré was the boiling point of water and that is how history records he calibrated his thermometers. The Réaumur scale was very popular in Europe in the 18th century and beyond.

2.3.3. The Celsius (Centigrade) scale.

Anders Celsius (1701–1744) was a Swedish astronomer. He used mercury in his thermometers which he introduced in 1741. He used two fixed points and an inverted scale with the melting point of ice (snow) set to be 100 ^{0}C and boiling water set to be 0 ^{0}C. This scale was reversed quite early on – reputedly by Swedish botanist Carolus Linnaeus (1707–1778) around 1745. The interested reader is referred to [1] for more details on Fahrenheit, Réaumur and Celsius.

So by the beginning of the 1800s thermometers were calibrated generally using one or more of these scales and manufactured in a sufficiently standardised way so that reliable temperature measurement was able to be performed. However, the actual numbers on the scales were still arbitrary – even the temperatures assigned to the fixed points were arbitrary. It was not until the middle of the 19th century with the advent of classical thermodynamics *and* a grasp of the importance of the "air thermometer" that physical meaning began to be ascribed to the measured temperatures.

3. The air thermometer and the emergence of classical thermodynamics

3.1. The air thermometer

Winding the clock back, alongside the liquid-in-glass thermometers that became the dominant way of measuring temperature as described earlier there was also research performed on using air as a thermometric fluid. For example, Robert Boyle (1627–1691) established the law named after him that for a closed system of a gas at constant temperature, the product of pressure (P) and volume (V) is constant, i.e. PV = Constant. This formulation would prove incredibly fruitful in later centuries as it is the foundation of constant volume primary thermometry.

How was air used as a thermometer? Consider figure 5 which is an early air thermometer design attributed to the French scientist Guillaume Amontons (1663–1705) (one of the first to recognise the existence of absolute zero of temperature). In the glass bulb was trapped air and above it was a quantity of mercury which partially filled the tube. If the temperature of the trapped air increased, the air pressure increased and the mercury in the column rose. Conversely if the temperature of the trapped air fell, the air pressure in the bulb decreased and the mercury fell. It was realised that such a device was sensitive to air pressure as well (being open) – but this was quickly overcome by filling it as a siphon and then sealing the end. Another issue was moist air trapped in the bulb, but when precautions were taken to ensure the air was dry reproducible temperature values could be obtained.

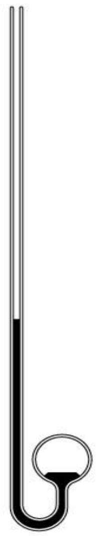

Figure 5. Early air thermometer design (c. 1690s) attributed to Amontons.

Exhaustive experimental research into whether air thermometers or liquid in glass thermometers were superior was undertaken in the 1840s in Paris by the formidable French experimentalist Henri Regnault (1810–1878). He quickly demonstrated that the air thermometer was far superior to the liquid-in-glass thermometer, showing, for example, that an air thermometer containing air at different densities or even different gases such as hydrogen indicated the same temperatures when the same amount of heat was applied. He published his seminal work in 1847 on "*Comparability of Gas Thermometers*" [5]. At

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that time a constant volume gas thermometer containing air gave the best approximation to the ideal gas law. However, air is a mixture of gases and to improve the approximation to the ideal gas law modern primary gas-based thermometers use pure inert gases such as argon or helium instead of air. During this work in Paris a young British scientist came (in 1845) and worked alongside Regnault: one William Thomson (better known now as Lord Kelvin), who was just a few years later to utterly transform the understanding of temperature.

3.2. Classical thermodynamics

William Thomson (1824–1907) was one of the last great classical physicists, making key advances in thermodynamics, electromagnetism and the practical application of physics. In 1846 at the young age of 22 he was appointed to the Chair of Natural Philosophy at the University of Glasgow. After his time in Paris and on his appointment at the University of Glasgow he set about trying to establish a fundamental theoretical framework for temperature. For this he used as a basis the Carnot cycle of an ideal heat engine (the interested reader is referred to [6] for technical details). However, it was through collaboration with James Joule (in the early to mid-1850s) that Thomson developed a robust theoretical framework for thermometry. In particular he formulated the following key concepts: that an absolute temperature scale existed (namely, one that is independent of the substance used in the thermometer), that there was such a thing as an absolute zero of temperature and through the encouragement of Joule, that heat and mechanical work were inter-convertible (essentially agreeing that energy is conserved). It was through this great work [7] that the foundation of primary thermometry was firmly established. It was only later in the century through the work of James Clerk Maxwell (1831–1879) and Ludwig Boltzmann (1844–1906) that the discipline of statistical mechanics emerged, showing that macroscopic observations are related to underlying microscopic behaviour; for example, temperature is directly related to the average kinetic energy of the particles of the (isothermal) system that was being measured, so it then follows from this that absolute zero is when particle motion ceases.

4. Emergence of modern thermometry: late 1800s to present day

The insightful theoretical work of William Thomson provided a sound foundation for primary thermometry, that is, thermometry based on fundamental physical principles, whilst the exhaustive experimental work of Henri Regnault pointed to a natural thermometer that could be used for primary thermometry – the gas thermometer.

But (and it is a **big** "but") primary thermometry is generally challenging and slow to undertake, requiring large apparatus as well as expert scientists to ensure the reliability of the results. One of the pioneers of practical resistance-based thermometry (H.L. Callendar, of whom more will be heard later) in fact said this of gas-based primary thermometry, "*It is impossible for those who have never worked with a gas thermometer to realise the extent of its shortcomings*" [8].

Nevertheless primary thermometry is still used today for fundamental temperature studies. For example in figure 6 is a photograph of one of the National Physical Laboratory (NPL)'s modern gas-based primary thermometers, an acoustic gas thermometer. Here the temperature of the gas is determined in pure argon through a measurement of the speed of sound in the gas. Whilst being exquisitely accurate it can hardly be said to be a practical thermometer since it can take one week to measure one temperature. Hence, whilst primary thermometry based on fundamental physics may be the purest approach to temperature measurement it certainly is not the most practical. So what to do? How to take advantage of the benefits of primary thermometry whilst retaining the benefits of practical temperature measurement?

This conundrum was addressed through three main events (some details are glossed over here for the sake of brevity; see [9] for more background). The first was the invention and promotion of an electrical-based (platinum) resistance thermometer [10], the second was the establishment of the International System of Units (the SI) and the third was one of the fruits of the SI, namely the global standardisation of temperature measurement through the establishment of the first defined scale – the International Temperature Scale of 1927 (ITS-27) [11].

Figure 6. Photograph of the NPL Primary Acoustic Gas Thermometer – courtesy of National Physical Laboratory.

The requirement for reliable temperature measurement grew in the latter half of the 18th century especially in industry. The use of liquid-in-glass thermometers was common but cumbersome and limited in temperature range, whilst the air thermometer was impractical. Developments of electrical-based thermometry were significant because the thermometers could be read remotely and had a much wider temperature range of operation. One whose sensing element was pure platinum was of particular importance and promoted by H. L. Callendar (1863–1930) [8], [10], [12]. As an aside Callendar's prowess as an experimentalist is celebrated annually by the UK Institute of Measurement and Control (InstMC) making an award in his honour for outstanding contributions to the art of instrumentation or measurement. It was through Callendar's work (and that of others) that the idea of calibrating a platinum resistance thermometer against a gas thermometer or against fixed points of known thermodynamic temperature was born. This approach would greatly facilitate practical temperature measurement, providing temperature values that were close (indeed very close) to thermodynamic temperature.

The International System of Units (the SI) [13] was brought into being in 1875 through the signing of the Metre Convention by seventeen nations, establishing the International Bureau of Weights and Measures (BIPM) which resides in the suburbs of Paris at Sèvres. At the time the SI formally only included the units of mass (the kilogram) and length (the metre). But eventually five other units were brought into the SI system; time (the second), temperature (the kelvin), electric current (the ampere), luminous intensity (the candela) and amount of substance (the mole). Today the SI system has become the *de facto* global measurement system of units with almost all (around 98 %) of the global economic activity underpinned by traceability to the SI.

The impetus the SI system gave to standardisation of measurements worldwide is of immeasurable significance. In the case of temperature, although the kelvin was only adopted as a formal base unit of the SI in 1954, temperature measurement was of great concern from the early days of the BIPM. It was in 1927 at the General Conference of Weights and Measures (CGPM) [11] that the first defined International Temperature Scale was established (the ITS-27) with a large part of the scale realised and disseminated through use of the platinum resistance thermometer developed by Callendar. This resistance thermometer was calibrated at a number of fixed points, examples including the liquefaction point of pure oxygen, the melting and boiling points of water and the sulphur boiling point, all the temperatures of which having been determined *a priori* by primary (gas [mainly hydrogen]) thermometry methods.

The chief benefit of this (in fact any) defined scale, rather than one that is based on thermodynamic approaches, is that it is simple to realise – it does not require a major physics experiment to establish – and it is reproducible. That is, if the "recipe" for establishing the scale is followed it will be the same wherever it is set up and that with very low uncertainties. For example, at modest and low temperatures uncertainties of 0.001 ^{o}C or lower are possible. One other benefit is that the temperatures given by the defined scale are very close to thermodynamic temperature via the calibration at the fixed points. Again at modest and low temperatures for the most recent defined scale (see below), the worst deviation between the defined scale and thermodynamic temperature is only of order 0.01 ºC. Indeed to all practical purposes the defined scale and thermodynamic temperature are equivalent.

Once the temperature scale had been established in the National Measurement Institutes (NMI) (like NPL in the UK) it was then a simple matter to calibrate reference thermometers for users from which they could then obtain a reliable temperature scale for themselves.

This basic pattern has been followed from 1927 until the present day. There have been iterations of the temperature scale with new ones introduced in 1948, 1968 and 1990, the current scale in use being the International Temperature Scale of 1990 [ITS-90]. With each iteration the closeness of the defined scale to thermodynamic temperatures has improved and the uncertainty in realisation of the scale has decreased to the point that for all practical purposes temperatures derived using the ITS-90 meet the vast majority of users' needs. The interested reader can find out more about the ITS-90 from the BIPM website [14]. Table 1 lists the ITS-90 elemental fixed points mainly used for calibrating platinum resistance thermometers with their defined thermodynamic temperatures and thermodynamic uncertainties (note that the ITS-90 temperatures are defined exactly so have no uncertainties). To convert the thermodynamic temperature into a degrees Celsius the value 273.15 needs to be subtracted from the temperature given in kelvin in table 1.

Table 1. The ITS-90 fixed points used to calibrate platinum resistance thermometers (except the gold and copper freezing points which are used to establish a high temperature radiance-based scale) with their thermodynamic temperatures and thermodynamic uncertainties.

Fixed point	ITS-90 temperature/K	Thermodynamic uncertainty/mK
Triple point of Neon	24.5561	0.5
Triple point of Oxygen	54.3584	1
Triple point of Argon	83.8058	1.5
Triple point of Mercury	234.3156	1.5
Triple point of water	273.16	0
Melting point of Gallium	302.9146	1
Freezing point of Indium	429.7485	3
Freezing point of Tin	505.078	5
Freezing point of Zinc	692.677	13
Freezing point of Aluminium	933.473	25
Freezing point of Silver	1234.93	40
Freezing point of Gold	1337.33	50
Freezing point of Copper	1357.77	60

Figure 7 shows a photograph of the sensing element of a modern standard platinum resistance thermometer. Figure 8 shows a sectioned metallic fixed point in this case based on the freezing point of pure tin. The graphite crucible holding the fixed point material would be inserted into a uniform furnace and then heated until all the metal was melted. The crucible would then be cooled and freezing initiated. The freezing point would be used to provide a reference of temperature against which the platinum resistance thermometer was calibrated, the temperature of the tin being defined on the ITS-90. Figure 9 shows a typical freezing curve of a modern high performance tin fixed point as measured by a standard platinum resistance thermometer – note that the resolution is of the order of 0.0001 ºC. The performance of these modern fixed points, that is those that have a clear phase transition at a fixed temperature (e.g. melting or freezing metal) or a triple point (one where the solid, liquid and gaseous phase of the substance co-exist such as the triple point of water), is many orders of magnitude better than for the first "fixed points" that were used [3, p10].

Figure 7. Photograph of a sensing element of a modern standard platinum resistance thermometer – courtesy of ISOTECH.

Figure 8. Section through a modern metallic (in this case tin) fixed point. The pure metal is contained within a graphite crucible. The thermometer being calibrated is inserted down the central well – courtesy of National Physical Laboratory.

Things have come a long way from qualitative thermometry with thermoscopes in the late 1500s to modern high technology temperature measurement performed robustly on a global basis. But is that the end of the story regarding reliable temperature measurement? Are there no more innovations to be made? The short answer is no! The closing section of the paper will discuss the kelvin redefinition and how that has stimulated exciting developments in modern thermometry which could lead to practical primary thermometry in a wide range of settings.

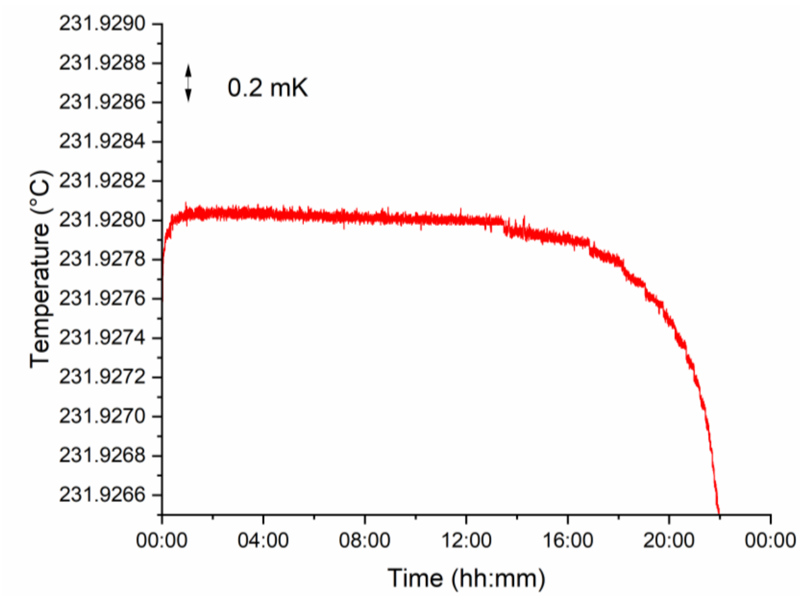

Figure 9. Freezing curve of a tin point – courtesy of National Physical Laboratory.

5. The kelvin redefinition and practical primary thermometry

5.1. The kelvin redefinition

On 20th May 2019 a momentous change occurred to the measurement system around the world even if almost unnoticed by the vast majority of people! On that day the SI measurement system was radically revised so that most of the SI units were thenceforth defined in terms of fundamental constants rather than physical artefacts [13]. The unit of temperature, the kelvin, had since 1954 been defined in terms of a fixed value of the triple point of water (273.16 K). From May 2019 it was defined in terms of a fixed value of the Boltzmann constant, k (1.380 649 $\times 10^{-23}$ J K^{-1}) [15]. This fundamental shift freed the kelvin definition from the quasi-artefact of the water triple point and stimulated the drive towards developing methods of providing temperature traceability directly to the kelvin by primary thermometry instead of the defined scales. This change in traceability is shown in figure 10. So for example, instead of providing temperature traceability to users by calibrating a standard platinum resistance thermometer (SPRT) at several fixed points the thermodynamic temperatures of which have been assigned by historic primary thermometry measurements (defined scale approach, figure 10a), the SPRT could instead be calibrated directly in terms of thermodynamic temperature in primary thermometry apparatus developed for that purpose (figure 10b). The interested reader can consult [16], [17] for more details on this change and its implications, but working towards this goal will take many years, certainly into the 2030s and beyond.

Whilst representing an important change this new approach still means that traceability is provided by linkage to a National Measurement Institute. However, to take full benefit from the kelvin redefinition the possibility of providing *direct* traceability to the kelvin in the place where the user needs it through development of practical primary thermometry is being developed.

5.2. Direct in-situ traceability to the kelvin through practical primary thermometry

To have practical sensors that measure thermodynamic temperature (that given by fundamental physical equations such as the gas law) at the point where they are needed is the "Holy Grail" of thermometry. It in approach is a major advance because the temperature is directly determined from the known physics associated with the measurement itself (some examples are given below). The great benefit of doing this is that the sensor would not need calibration before installation and the user would be able to rely on the sensor's temperature values during its lifetime (unlike now where regular re-calibration is required to compensate for sensor drift and ensure ongoing validity of measurement). The shortened traceability arrangement is shown in figure 10c.

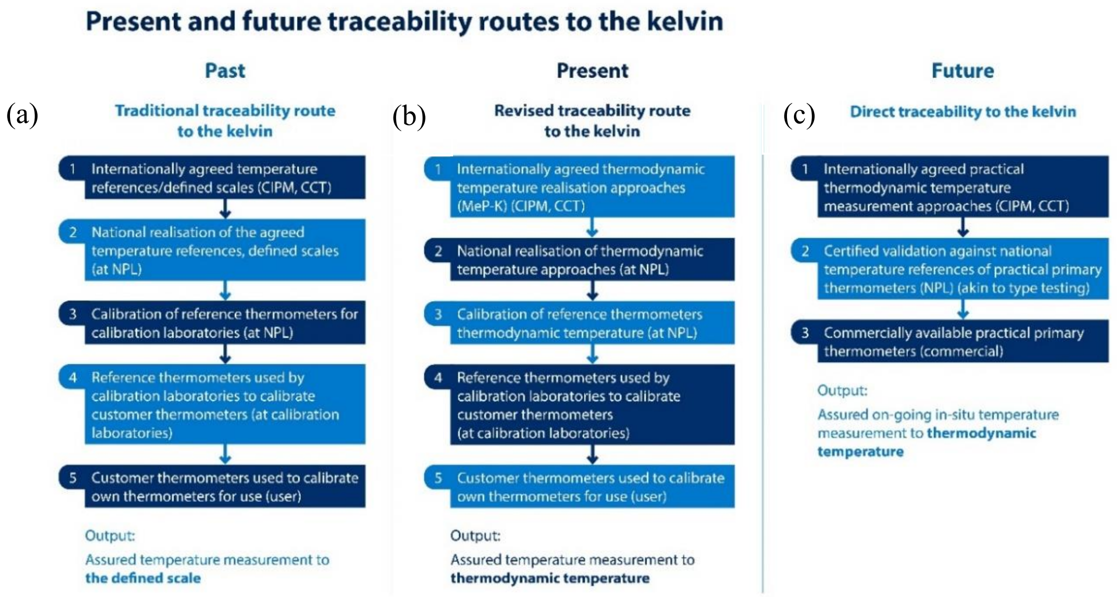

Figure 10. Establishing traceability for reliable temperature measurement: present (a, left), near-term (b, middle) and long-term (c, right).

Direct *in-situ* traceability was for a long time thought impractical and still is for the more classical gas-based primary thermometry approaches. However, modern technology has come to the rescue and new primary thermometry approaches are emerging that are potentially able to form an easier-to-implement basis of practical temperature sensing in the future. Three will be briefly mentioned below.

- Johnson Noise Thermometry. Johnson Noise is the mean-square voltage that is generated in a resistor by the random thermal motion of the electrons contained within it. The thermodynamic temperature is a function of the square of this voltage. The theory has been known for a long time but the voltage, being very small, has always been challenging to measure. Now with advances in modern voltage measurement techniques such a device is becoming practical [18].
- Ring-Resonator Thermometry. This approach microfabricates coupled miniscule (~10 microns in diameter) optical resonators on to semi-conductor material. Light of a particular frequency is passed through one ring and this then couples evanescently to the second ring. The frequency of the light is then scanned (or tuned) to initiate resonant coupling in the second ring. The frequency of the induced resonance depends on the ring temperature (and by implication the temperature of the microchip on which it resides) and so can be used to determine temperature [19].
- Doppler Broadening Thermometry. This approach passes laser light through an optical cell containing atoms which have a spectral transition corresponding to the laser line. The line is broadened by the thermal motion of the atoms in the optical cell. The temperature of the atoms is then determined from how much the line is broadened. If the cell is coupled to the laser and measurement system by fibre-optic cables, then the optical cell forms a thermometer [20].

These approaches whilst some way off practical application (for some maybe even a decade or more) represent a paradigm shift in how temperature is measured. This holds out the prospect of *in-situ* reliable temperature measurement in the most challenging of settings.

6. Summary

This paper has covered the progress of temperature measurement from its emergence in the late 1500s to prospects for practical primary thermometry in the future ((next 20+ years). Starting from zero knowledge reasonably reliable temperature measurement was well established by the late 1700s with only three main scales generally in use at the turn of the 1800s. Innovations by William Thomson in the 1850s led to a deeper, more physical understanding of temperature leading to its measurement for the first time having a sound underlying physical basis. Then in the early 1900s the establishment of defined temperature scales linked to thermodynamic temperature meant that reliable temperature measurement on a global basis became possible. Refinements were made during the 20th and early 21st century but now with the kelvin redefinition the stage is set for the final step in thermometry development begun all those years ago, namely practical primary thermometers linked directly to the physics of the measurement setting that will provide *in-situ* reliable thermodynamic temperature values throughout the sensor lifetime.

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