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The Thermometer—From The Feeling To The Instrument

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Abstract: The thermometer, as we know it today, is the result of a long trial and error process. It began with a physiological description of temperature and evolved to the present state. The different stages in its development reflect the state of science at the time as well as the ingenuity of scientists to realize and overcome the shortcomings of science during each stage.

The thermometer is probably one of the first measuring instruments with which we become familiar; nevertheless, the accurate measurement of temperature is a rather new concept, dating from only 150 to 250 years ago. In this work we will trace the concept of heat and cold from ancient times to its establishment in quantitative terms and expression through the proper instrument.

The physiological sensation of hot and cold has been with mankind from the very beginning. Noah, in the tenth generation after Adam, is told after he comes out of the Ark that the natural order before the Deluge will return: "While the earth remaineth, seeding time and harvest, cold and heat, summer and winter, and day and night shall not cease" (Genesis 8:22). Observations of various natural and man-made phenomena led the ancients to postulate theories that led to our modern concepts of the nature of heat and heat transfer. Thermometry started from the recognition of the need to quantify the differences more precisely than by using adjectives like hot and cold. Claudius Galen (130–201 A.D.) based much of his treatment of the sick on the theory that individual difference, whether of sickness and health, of body habits, or of racial origin were in fact differences in the proportion of the four essential qualities: heat, cold, moisture, and dryness, as was postulated by Aristotle and other philosophers. Galen quantified the concept of degrees of hot and cold to indicate the extent to which these qualities were present in a body and suggested a mixture of equal bulks of boiling water and ice to fix a standard of *neutral* temperature. According to Galen, at the neutral temperature the concepts of hot and cold become identical. During his time, the *complexion* of a person was determined by the proportion in which heat, cold, moisture, and dryness were tempered, giving origin to the word *temperament*. This has not changed much from its original meaning, and *temperature*, which today has a precise physical meaning, meant, until the 18th century, the tempering of the qualities in a substance [1].

The ancient physiological concepts of hot and cold have evolved considerably in the last 2000 years. Today, we formulate the idea of temperature using the Zeroth Law of Thermodynamics, which states that if a system, A, is in thermal equilibrium with another system, B, and if system B is in thermal equilibrium with a third system, C, then system C is also in thermal equilibrium with system A. From the zeroth law we go on to say that for two or more systems to be in thermal equilibrium there must exist an intensive property that is a function of the state of any system and which has the characteristic of having an identical value for every system. This property is called *temperature*. There are a number of definitions of temperature. According to thermodynamics, it is the property that determines whether a given system is in thermal equilibrium with other systems. Temperature is one of the seven basic physical properties in terms of which all other physical quantities are defined. It differs from the others by being an intensive property, whereas the other six (length, mass, time, electric current, amount of a substance, and luminous intensity) are extensive properties. A temperature scale established according to the zeroth law is known as an *empirical temperature scale*. The correlation of hotter states with larger and positive temperatures and of colder states with lower or negative temperatures is achieved by a suitable choice of the thermometric function together with fixed thermometric points. The position of $T = 0$ is also arbitrary and depends on the same choices. Today, these ideas seem obvious and not subject to discussion. Let us now analyze how they developed from their crude definition in ancient times to their present status. We will first define a thermometer simply as any class of instrument that measures temperature. As will be shown below, temperature has usually been measured in an indirect form, using a property of a substance that changes with temperature, like phase equilibrium, expansivity of a gas or liquid, electrical resistively, heat radiation, etc.

We can distinguish three different stages in the development of the thermometer; each corresponds to a scientific barrier that had to be overcome. These stages are (1) open thermometers, (2) closed thermometers, and (3) calibration.

Open Thermometers

The impulse to improve thermometry came largely from the study of weather [2]. The liquid-in-glass thermometer was a meteorological instrument before it was used for chemistry and physics. The ancient Greeks did visualize degrees of hot and cold and performed experiments that could be considered as the basis of a thermometer; however, it was not until the late 16th century that the first thermoscope (a thermometer without a scale) appeared. Although there are many claims to who built the first thermoscope, most authorities attribute its invention to the Italian scientist Galileo (1564–1642), probably in 1592. There are independent reports of air thermoscopes invented by Galileo's medical disciple, Sanctorius (1561–1636); the

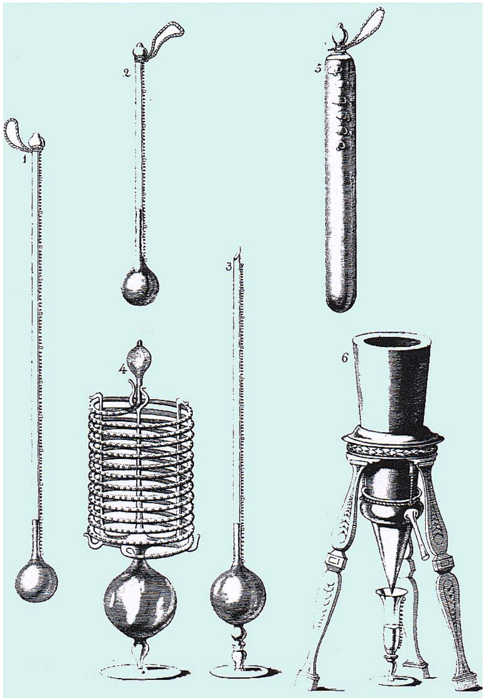

Figure 1. Thermometers (1–5) and a hygrometer (6) of the Accademia del Cimento. (From Middleton [2]).

physician and mystical philosopher, Robert Fudd (1574–1651); the clock maker, Cornelius Drebbel (1572–1633); and the engineer, Salomon de Caus [1]. The first thermometers had the common property of being a tube of different construction opened to the atmosphere. They either did not have a scale, or they were crudely graduated with notches. They were usually intended for medical or meteorological purposes. The thermometers built by Evangelista Torricelli (1608–1647) had blown glass bubbles of different weight; the ball that floated determined the particular level of temperature. None of the scales were comparable with other instruments or accurate from one day to the other because of changing barometric conditions. The earliest air thermometer that corrected for air pressure seems to be the one described by Guillaume Amontons (1663–1705) to the Académie des Sciences in 1702 [2].

Closed-Glass Liquid Thermometers

Early on, the manufacturers of thermometers observed that temperature readings were affected by fluctuations in the barometric pressure. Around 1654, Leopoldo (1610–1670), Cardinal de Medici, a cofounder with his brother, Leopold II, of the Accademia del Cimento (Academy of Experiments), made the first closed-glass liquid thermometers, known as Florentine thermometers. These instruments consisted of a glass tube closed at one end and having a liquid reservoir of large dimensions in the shape of a bulb at the other. The Academy conducted extensive thermometric experiments and its members became highly skilled in the manufacture of thermometers of reproducible dimensions. These thermometers, widely used in France and England, were graduated into 50, 100, or 300 degrees and used distilled colored wine as the thermometric fluid. The instruments were roughly standardized by the heat of the sun and the cold of ice water; every degree was marked in the tube by an enamel point, white for every 10-degree mark and black for the others. The advantage of a liquid like wine was that its expansion was independent of air pressure. Mercury and water thermometers were also tried by the Florentines but abandoned because their expansion was too small. Later, this problem was overcome by the simple solution of making thermometers with finer bores, thereby increasing their sensitivity.

By the middle of the 18th century mercury thermometers had superceded others because of their more uniform expansion. An important advantage of mercury was that, unlike other thermometric fluids, it was available in a high state of purity. The appearance of the thermometer in the 17th century provoked the semantic evolution of the word *temperature* instead of the term *temperament* used by physicians of the period; the new word takes its present significance and replaces little by little the expression *degree of heat*. It seems that in 1624 the French Jesuit Jean Leurechon (1593–1670) was the first to introduce the word *thermometer* to describe an instrument for measuring the degree of heat or cold present in air. A Latin manuscript published in 1611 gives the name *thermoscopium* to the instrument designed by Sanctorius. The works of Taylor [1], Middleton [2], and Brown [3] have some fascinating sketches illustrating earlier thermometers (see Figure 1).

Calibration Scales

By about 1660 the spirit-in-glass thermometer had been brought to a technically satisfactory state and the mercury-in-glass thermometer had been tried and temporarily abandoned. The next stage in the development was the attempt to make thermometers universally comparable. A basic requirement of thermometers, obvious today, but not so in the Middle Ages, is that different instruments must give identical readings. Manufacturing identical thermometers can solve the problem, but this solution presents great difficulties in fabrication. A far more feasible method consists in rendering nonidentical instruments that are made comparable by a process of calibration using the concept of a fixed point or reference state [4]. The concept of the fixed point is a practical consequence of the zeroth law. If two different thermometers are put in contact with, say, ice at its normal melting point, then their readings must reflect the fact that the two thermometers and the ice have the same temperature and that both thermometers are in thermal equilibrium with the ice. For example, in the 17th century Francesco Sagredo defined three fixed points to calibrate his thermometers: the greatest summer heat, snow, and a mixture of snow and salt were labeled, 360, 100, and 0 degrees, respectively. By the early 18th century as many as 35 temperature scales had been devised, most of them based upon either or both of the following two principles: (a) calibration of the instrument at two temperatures and division of the interval into equal parts and (b) calibration of the instrument at one temperature with subsequent scale division based upon the calculated expansion of the thermometric fluid. Once this understanding was achieved, attention was paid to standardizing scales of temperature by marking off heat levels of specified natural phenomena. At first, the number of reference points used was very large, and included, among others, the equilibrium temperature of ice water and various salts, the melting point of butter or wax, the candle flame, the temperature of the first night frost, the temperature of deep cellars and mines, and even the temperature of the basement of the Paris Observatory (28 meters underground!) [2, 4]. As a historical curiosity we can mention that both Galileo and Boyle believed that the temperature of places like deep cellars and mines, etc. remained quite constant [4]. Three other fixed points were frequently used, the boiling and freezing points of water and the normal body temperature. The list of contributors to the solution of this problem includes many of the famous scientists of the period, like Robert Boyle (1627–1691), Robert Hooke (1635–1703), Isaac Newton (1642–1727), and Christian Huygens (1629–1695). For example, in 1701 Newton suggested the use of two fixed points to determine the thermometric scale. Newton labeled the melting point of ice as 0 ° and the armpit temperature of a healthy Englishman as 12 °. On this scale water boiled at 34 °. His thermometric fluid was linseed oil.

The Danish astronomer Rømer (1644–1710), discoverer of the finite speed of light, is assumed to be the first to build reproducible thermometers. In 1702 he proposed using two fixed points. The lower fixed point, corresponding to the temperature of an artificial mixture of salt, water, and ice, was assigned the value 0 °, while the steam point was the upper fixed point and marked as 60 °. The resulting scale was divided into equal increments of volume, numbered from 8 to 59. (Rømer took careful steps to check the uniformity of the bore by measuring the length of a mercury drop at various locations of the thermometer tube.) The Rømer scale was then sexagesimal (very appropriate for an astronomer), and on it the melting point of ice was 7.5 ° (changed later to 8 °). Because Rømer seldom used the upper part of the scale for his meteorological observations, he changed its upper reference temperature to that of blood heat, labeling it 22.5 ° (as reported by Fahrenheit). Rømer's scale is important because it became the basis of the one proposed by Fahrenheit.

Gabriel Daniel Fahrenheit (1686–1736) was born in Danzig and lived most of his life in Holland. In 1708 he visited Rømer and borrowed from him the idea of calibrating thermometers using the melting point of ice and the heat of blood as fixed points. The original thermometers of Fahrenheit used alcohol as the thermometric fluid, but later he switched to mercury. At the beginning Fahrenheit used the scale of Rømer, except that he added four more divisions to each degree. Later on, he decided that the values of the fixed points in the Rømer scale were inconvenient and awkward, and he multiplied them by four to give 30 ° for the normal ice point and 90 ° for body temperature. Later, he decided that 96 ° would be a more suitable body temperature because it would be divisible by 12 (and by 32). Soon afterwards, Fahrenheit developed a thermometer to measure boiling points at atmospheric pressure and found the boiling point of water to be 212 °. He, therefore, modified his scale to include the boiling point of water as the upper fixed point at 212 °. In order to give a more rational 180 ° interval between the two fixed points, he made the ice point 32 ° at 1 atm pressure. Body temperature is around 98.4 ° on this final version of the Fahrenheit scale. The excellent quality of the thermometers manufactured by Fahrenheit gained him admission to the Royal Society of London. There he announced in 1724 that he had constructed thermometers in which he had fixed 32 °F as the freezing point of water and 96 °F as normal body temperature. In this way he used a much finer scale than Rømer's original. It is interesting to note that, although the boiling point of water is 212 °F, it was not originally taken as a fundamental reference point, but it was widely adopted as such by about 1740 [2, 4]. The Fahrenheit scale was adopted in England and in the Low Countries but not in France, where the system proposed by Réamur prevailed. Fahrenheit thermometers manufactured after his death were already normalized using 32 ° for the melting point of ice and 212 ° for the boiling point of water.

At the same time, the French scientist Rene-Antoine Ferchault de Réaumur (1683–1757) proposed a different scale calibrated at one temperature only with subsequent scale divisions based upon the calculated expansion of the fluid in the thermometer. Réaumur made many experiments to select the proper thermometric fluid and settled on spirit of wine diluted with a certain amount of water because of its large dilation. The dilution selected was the one that gave a dilation of 80 in 1000, as heated from the temperature of freezing to the temperature of boiling water, because 80 is a "number convenient to divide in parts." Because of this selection the public came to believe that in the Réaumur scale water boiled at 80 °. Eventually, it became general practice to graduate the Réaumur thermometer using two fixed points, the freezing point (0 °) and the boiling point of water (80 °). An interesting point to mention is the large dimension of Réaumur's thermometers. They had a large bulb with a diameter of 81 to 108 mm to which was connected a long tube (1.30 to 1.62 m) of 6.8 to 9.0 mm internal diameter. As he wrote in his papers on the subject, he did not see any reason why not to build thermometers of very large dimensions. He actually suggested bulbs 13 mm in internal diameter with a tube up to 10 mm in bore. The thermometers and the scale proposed by Réaumur were used in France and central Europe for well over a century in spite of the decision of the French Revolution authorities to adopt the decimal system. A thermometer scale similar to that of Réaumur was invented in 1732 by Joseph Nicolas Delisle (1688–1768), a French astronomer who had been invited to Russia by Peter the Great. In that year he built a thermometer that used mercury as a working fluid. Delisle chose his scale using the temperature of boiling water as the fixed point and the number of hundred-thousandths of the volume mercury contracted at lower temperatures. The thermometers usually had 2,400 graduations, appropriate to the winter in St. Petersburg where Delisle lived. In 1738 Josias Weitbrecht (1702–1747) recalibrated the Delisle thermometer with 0 ° as the boiling point and 150 ° as the freezing point of water. The Delisle thermometer remained in use for almost 100 years in Russia [4].

Several attempts to transform the Delisle scale to a 100-degree interval were made before the Swedish astronomer Anders Celsius (1701–1744) proposed in 1741 to graduate thermometers with 100 ° as the boiling point of water and 0 ° as the melting point of snow. Apparently wishing to avoid the use of negative numbers for commonly encountered meteorological temperatures, Celsius assigned the number 100 to the freezing point of water and zero to the boiling point, dividing the intervening distance into 100 equal degrees. In 1745 his friend Carl Linnaeus inverted the scale to give us the now-familiar centigrade scale that matches the psychological feeling that hotter should correspond to a higher temperature. The general use of the Celsius scale in the 19th century was probably accelerated by the decision of the French Revolution authorities to adopt the decimal system for all measurable quantities. The Commission of Weights and Measures, created by the French Assembly, decided in 1794 that the thermometric degree will be 1/100 of the distance between the ice point and steaming water (originating the word centigrade). In October 1948 the IX Conference of Weights and Measures assigned the name degree Celsius to this unit.

The quality of the thermometer depends largely on the quality of the glass from which it is made. This fact had been common knowledge since the appearance of the Florentine thermometers. Fahrenheit recommended that to attain the best comparability different thermometers should be constructed of the same class of glass. The small thermal expansion of mercury thermometers makes the instrument very sensitive to the thermal behavior of glass. Inferior glass has a considerable thermal lag; that is, the volume change lags behind the temperature change reaching its final value only after several hours. Already in 1880 it was recommended that glasses containing lead oxide should be avoided. Glass also exhibits volume *hysteresis*; that is, its own volume depends not only on its present temperature but also on its past thermal history (during heating, the readings for a given temperature will be different than those for the same temperature when cooling). A glass thermometer heated to a high temperature and then cooled and placed in an ice bath seemingly comes immediately to equilibrium; however, the bulb continues to shrink, gradually causing a corresponding rise of the ice point. This is called *zero-point creep*. This progressive change of the ice point represents an asymptotic approach to some limiting bulb volume and, depending on the quality of the glass, may go on for a very long time. To illustrate this point we can mention that Joule (1818–1889) kept records for 40 years of the zero point of his thermometers. In 1844 he marked the freezing point of water as zero on a very accurate thermometer made by Dancer. Then, up to 1882, he determined the freezing point of water several times and noted that it has risen steadily up to 0.61 °C. When the thermometer was last examined in 1930, the creep was still in progress and had reached 0.67 °C. It was noted that the rate of rise had initially been rapid, but was slowing down and, it could be inferred, would ultimately be undetectable. Unfortunately, Joule’s thermometers were destroyed during an air raid in 1942. Although modern borax glasses are a great improvement over earlier glasses, they still exhibit creep. Zero-point creep renders the fixed points, and hence the whole scale of liquid-in-glass thermometers, uncertain and so precludes them as standards [5].

The demand for greater accuracy along with problems related to thermometric construction forced scientists to devise alternative techniques for measuring temperature. Deformation thermometers were an early choice. They indicate a change in temperature by a change in the shape or configuration of solid bodies. Thermometers based on the expansion of metal rods were tried as early as 1735 and led to the development of bimetallic instruments by the end of the 18th century. These instruments function on the principle that the difference of expansion of two metal strips welded together produces a bending that can activate a pointer on a dial calibrated against a standard mercury thermometer. Their invention greatly simplified the design of metallic thermometers, making them more compact and more sensitive.

Gas thermometers (based on Charles’ law) can also be used to measure temperatures higher than the upper limit of mercury thermometers (around 350 °C). Gas thermometers can be of two kinds: (a) constant-pressure thermometers that rely on volumetric measurement and (b) constant-volume thermometers based on pressure measurement. Extensive experimentation, performed first by Henri Regnault (1810–1878) and then by Pierre Chapuis, moved the standard of gas thermometry from an error of 0.1 °C to around 0.02 °C. In 1927 the General Conference on Weights and Measures decided upon the first International Practical Temperature Scale (IPTS) by comparing the results of the long story of practical thermometry with the half-century-old thermodynamic scale. Because of subsequent improvements in measurements and techniques, the IPTS of 1927 has been constantly updated through 1990 (IPTS-90, currently used). The IPTS-68 recognizes the thermodynamic temperature as the basic temperature and defines its unit (the kelvin) to be 1/273.16 of the triple point of water. The triple point temperature depends solely on the purity of the substance used, and is, in this respect, superior to the ice and steam points that depend not only on the purity but also on their pressure being held exactly at one atmosphere. On this basis, the size of the degree does not change owing to new and better measurements. The present choice assures that 1 degree on the Kelvin scale is nearly equal to one degree on the Celsius scale, the difference being so slight that even quite sensitive instruments cannot detect it.

Other Thermometers

Other useful forms of thermometry have been developed on the basis of electrical phenomena. Temperature measurements using thermocouples are based on the Seebeck effect that establishes that an electric current flows in a continuous circuit of two different metallic wires if the two junctions are at different temperatures. The resistance thermometer is based on the property that the electrical resistance of a metal changes when it undergoes a change in temperature. The well-known platinum resistance thermometer was studied and perfected in 1886 by Callendar. It found immediate wide use and now is the prime standard thermometer between 259 °C and +630 °C.

Conclusion

The thermometer, as we know it today, is the result of a long trial and error process that began with a physiological description of temperature and evolved to the present state of the art. The different stages in its development reflect the state of science at the time, as well as the ingenuity of scientists to realize and overcome the shortcomings of the state of science at each stage.

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