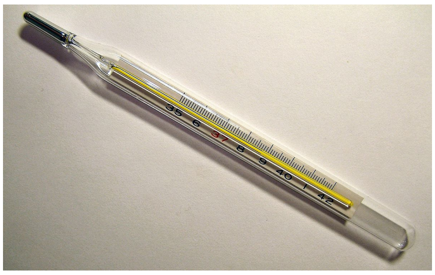
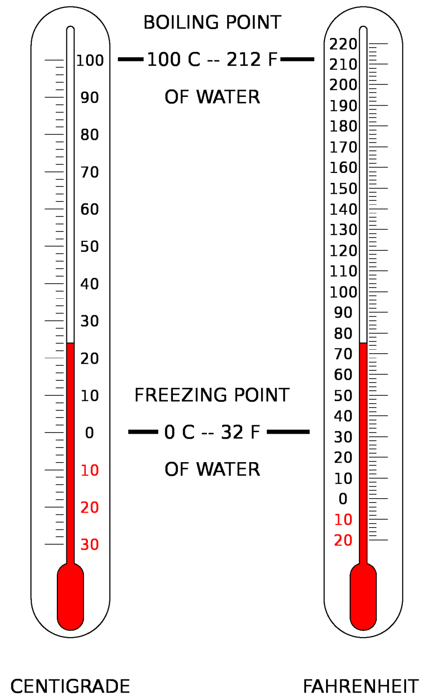
Thermometer

Developed during the 16th and 17th centuries, a **thermometer** (from the Greek *θερμός* (*thermo*) meaning "warm" and *meter*, "to measure") is a device that measures temperature or temperature gradient using a variety of different principles.[1] A thermometer has two important elements: the temperature sensor (e.g. the bulb on a mercury thermometer) in which some physical change occurs with temperature, plus some means of converting this physical change into a numerical value (e.g. the scale on a mercury thermometer).



A clinical mercury-in-glass thermometer

There are many types of thermometer and many uses for thermometers, as detailed below in sections of this article.



Thermometer

Temperature

While an individual thermometer is able to measure degrees of hotness, the readings on two thermometers cannot be compared unless they conform to an agreed scale. There is today an absolute thermodynamic temperature scale. Internationally agreed temperature scales are designed to approximate this closely, based on fixed points and interpolating thermometers. The most recent official temperature scale is the International Temperature Scale of 1990. It extends from 0.65 K (−272.5 °C; −458.5 °F) to approximately 1358 K (1085 °C; 1985 °F).

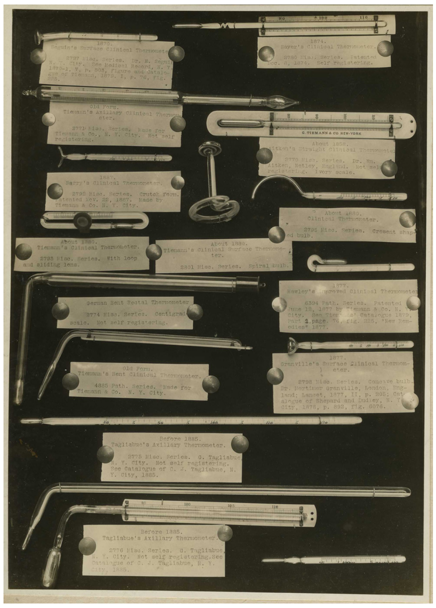
Development

Galileo thermometer

Various authors have credited the invention of the thermometer to Cornelius Drebbel, Robert Fludd, Galileo Galilei or Santorio Santorio. The thermometer was not a single invention, however, but a development.

Philo of Byzantium and Hero of Alexandria knew of the principle that certain substances, notably air, expand and contract and described a demonstration in which a closed tube partially filled with air had its end in a container of water.[2] The expansion and contraction of the air caused the position of the water/air interface to move along the tube.

Such a mechanism was later used to show the hotness and coldness of the air with a tube in which the water level is controlled by the expansion and contraction of the air. These devices were developed by several European scientists in the 16th and 17th centuries, notably Galileo Galilei.[3] As a result, devices were shown to produce this effect reliably, and the term *thermoscope* was adopted because it reflected the changes in sensible heat (the concept of temperature was yet to arise).[3] The difference between a thermoscope and a thermometer is that the latter has a scale.[4] Though Galileo is often said to be the inventor of the thermometer, what he produced were thermoscopes.



Various thermometers from the 19th century.

Galileo Galilei also discovered that objects (glass spheres filled with aqueous alcohol) of slightly different densities would rise and fall, which is nowadays the principle of the Galileo thermometer (shown). Today such thermometers are calibrated to a temperature scale.

The first clear diagram of a thermoscope was published in 1617 by Giuseppe Biancani: the first showing a scale and thus constituting a thermometer was by Robert Fludd in 1638. This was a vertical tube, with a bulb at the top and the end immersed in water. The water level in the tube is controlled by the expansion and contraction of the air, so it is what we would now call an air thermometer.[5]

The first person to put a scale on a thermoscope is variously said to be Francesco Sagredo[6] or Santorio Santorio[7] in about 1611 to 1613.

The word thermometer (in its French form) first appeared in 1624 in *La Récréation Mathématique* by J. Leurechon, who describes one with a scale of 8 degrees.[8]

The above instruments suffered from the disadvantage that they were also barometers, i.e. sensitive to air pressure. In about 1654 Ferdinando II de' Medici, Grand Duke of Tuscany, made sealed tubes part filled with alcohol, with a bulb and stem, the first modern-style thermometer, depending on the expansion of a liquid, and independent of air pressure.[8] Many other scientists experimented with various liquids and designs of thermometer.

However, each inventor and each thermometer was unique—there was no standard scale. In 1665 Christiaan Huygens suggested using the melting and boiling points of water as standards, and in 1694 Carlo Renaldini proposed using them as fixed points on a universal scale. In 1701 Isaac Newton proposed a scale of 12 degrees between the melting point of ice and body temperature. Finally in 1724 Daniel Gabriel Fahrenheit produced a temperature scale which now (slightly adjusted) bears his name. He could do this because he manufactured thermometers, using mercury (which has a high coefficient of expansion) for the first time and the quality of his production could provide a finer scale and greater reproducibility, leading to its general adoption. In 1742 Anders Celsius proposed a scale with zero at the boiling point and 100 degrees at the melting point of water,[9] though the scale which now bears his name has them the other way around.[10]

In 1866 Sir Thomas Clifford Allbutt invented a clinical thermometer that produced a body temperature reading in five minutes as opposed to twenty.[11] In 1999 Dr. Francesco Pompei of the Exergen Corporation introduced the world's first temporal artery thermometer, a non-invasive temperature sensor which scans the forehead in about 2 seconds and provides a medically accurate body temperature.[12] [13]

Old thermometers were all **non-registering thermometers**. That is, the thermometer did not hold the temperature after it was moved to a place with a different temperature. Determining the temperature of a pot of hot liquid required the user to leave the thermometer in the hot liquid until after reading it. If the non-registering thermometer was removed from the hot liquid, then the temperature indicated on the thermometer would immediately begin changing to reflect the temperature of its new conditions (in this case, the air temperature). **Registering thermometers** are designed to hold the temperature indefinitely, so that the thermometer can be removed and read at a later time or in a more convenient place. The first registering thermometer was designed and built by James Six in 1782, and the design, known as Six's thermometer is still in wide use today. Mechanical registering thermometers hold either the highest or lowest temperature recorded, until manually re-set, e.g., by shaking down a mercury-in-glass thermometer, or until an even more extreme temperature is experienced. Electronic registering thermometers may be designed to remember the highest or lowest temperature, or to remember whatever temperature was present at a specified point in time.

Thermometers increasingly use electronic means to provide a digital display or input to a computer.

Physical principles of thermometry

Thermometers may be described as empirical or absolute. Absolute thermometers are calibrated numerically by the thermodynamic absolute temperature scale. Empirical thermometers are not in general necessarily in exact agreement with absolute thermometers as to their numerical scale readings, but to qualify as thermometers at all they must agree with absolute thermometers and with each other in the following way: given any two bodies isolated in their separate respective thermodynamic equilibrium states, all thermometers agree as to which of the two has the higher temperature, or that the two have equal temperatures. For any two empirical thermometers, this does not require that the relation between their numerical scale readings be linear, but it does require that relation to be continuous and strictly monotonic. This is a fundamental character of temperature and thermometers.[14] [15] [16]

As it is customarily stated in textbooks, taken alone, the so-called 'zeroth law of thermodynamics' fails to deliver this information, but the statement of the zeroth law of thermodynamics by Serrin in 1977, though rather mathematically abstract, is more informative for thermometry: "Zeroth Law - There exists a topological line M which serves as a coordinate manifold of material behaviour. The points L of the manifold M are called 'hotness levels', and M is called the 'universal hotness manifold'."[17] To this information there needs to be added a sense of greater hotness; this sense can be had, independently of calorimetry, of thermodynamics, and of properties of particular materials, from Wien's displacement law of thermal radiation: the temperature of a bath of thermal radiation is proportional, by a universal constant, to the frequency of the maximum of its frequency spectrum; this frequency is always positive, but can have values that tend to zero.

There are several principles on which empirical thermometers are built, as listed in the section of this article entitled 'Primary and secondary thermometers'. Several such principles are essentially based on the constitutive relation between the state of a suitably selected particular material and its temperature. Only some materials are suitable for this purpose, and they may be considered as 'thermometric materials'. Radiometric thermometry, in contrast, can be only very slightly dependent on the constitutive relations of materials. In a sense then, radiometric thermometry might be thought of as 'universal'. This is because it rests mainly on a universality character of thermodynamic equilibrium, that it has the universal property of producing blackbody radiation.

Thermometric materials

There are various kinds of empirical thermometer based on material properties.

Many empirical thermometers rely on the constitutive relation between pressure and volume and temperature of their thermometric material. For example, mercury expands when heated.

If it is used for its relation between pressure and volume and temperature, a thermometric material must have three properties:

(1) its heating and cooling must be rapid. That is to say, when a quantity of heat enters or leaves a body of the material, the material must expand or contract to its final volume or reach its final pressure and must reach its final temperature with practically no delay; some of the heat that enters can be considered to change the volume of the body at constant temperature, and is called the latent heat of expansion at constant temperature; and the rest of it can be considered to change the temperature of the body at constant volume, and is called the specific heat at constant volume. Some materials do not have this property, and take some time to distribute the heat between temperature and volume change.[18] A simple home experiment with a microwave oven heating some water will illustrate what is meant here; take great care not to scald yourself with this experiment; a mistake can give a severe burn.

(2) its heating and cooling must reversible. That is to say, the material must be able to be heated and cooled indefinitely often by the same increment and decrement of heat, and still return to its original pressure and volume and temperature every time. Some plastics do not have this property;[19]

(3) its heating and cooling must be monotonic. That is to say, throughout the range of temperatures for which it is intended to work, (a) at a given fixed pressure, either (α) the volume increases when the temperature increases, or else (β) the volume decreases when the temperature increases; not (α) for some temperatures and (β) for others; or (b) at a given fixed volume, either (α) the pressure increases when the temperature increases, or else (β) the pressure decreases when the temperature increases; not (α) for some temperatures and (β) for others.

At temperatures around about 4C, water does not have the property (3), and is said to behave anomalously in this respect; thus water cannot be used as a material for this kind of thermometry for temperature ranges about 4C.[20] [21] [22] [15]

Gases, on the other hand, all have the properties (1), (2), and (3)(a)(α) and (3)(b)(α). Consequently, they are suitable thermometric materials, and that is why they were important in the development of thermometry.[23]

Constant volume thermometry

According to Preston (1894/1904), Regnault found constant pressure air thermometers unsatisfactory, because they needed troublesome corrections. He therefore built a constant volume air thermometer.[24] Constant volume thermometers do not provide a way to avoid the problem of anomalous behaviour like that of water about 4 C.[22]

Radiometric thermometry

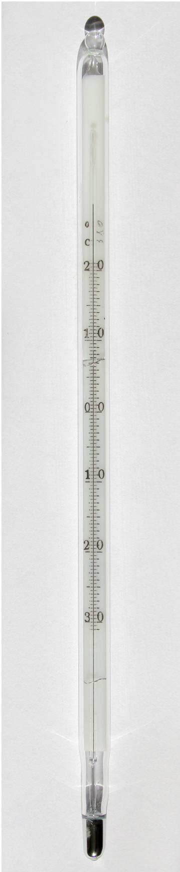
Planck's law very accurately quantitatively describes the power spectral density of electromagnetic radiation, inside a rigid walled cavity in an body made of material that is completely opaque and poorly reflective, when it has reached thermodynamic equilibrium, as a function of absolute thermodynamic temperature alone. A small enough hole in the wall of the cavity emits near enough blackbody radiation of which the specific radiative intensity can be precisely measured. The walls of the cavity, provided they are completely opaque and poorly reflective, can be of any material indifferently. This provides a well-reproducible absolute thermometer over a very wide range of temperatures, able to measure the absolute temperature of a body inside the cavity.

Primary and secondary thermometers

Thermometers can be divided into two separate groups according to the level of knowledge about the physical basis of the underlying thermodynamic laws and quantities. For **primary thermometers** the measured property of matter is known so well that temperature can be calculated without any unknown quantities. Examples of these are thermometers based on the equation of state of a gas, on the velocity of sound in a gas, on the thermal noise (see Johnson–Nyquist noise) voltage or current of an electrical resistor, on blackbody radiation, and on the angular anisotropy of gamma ray emission of certain radioactive nuclei in a magnetic field. Primary thermometers are relatively complex.

Secondary thermometers are most widely used because of their convenience. Also, they are often much more sensitive than primary ones. For secondary thermometers knowledge of the measured property is not sufficient to allow direct calculation of temperature. They have to be calibrated against a primary thermometer at least at one temperature or at a number of fixed temperatures. Such fixed points, for example, triple points and superconducting transitions, occur reproducibly at the same temperature.

Calibration


Mercury laboratory thermometer

Thermometers can be calibrated either by comparing them with other calibrated thermometers or by checking them against known fixed points on the temperature scale. The best known of these fixed points are the melting and boiling points of pure water. (Note that the boiling point of water varies with pressure, so this must be controlled.)

The traditional method of putting a scale on a liquid-in-glass or liquid-in-metal thermometer was in three stages:

1. Immerse the sensing portion in a stirred mixture of pure ice and water at 1 Standard atmosphere (101.325 kPa; 760.0 mmHg) and mark the point indicated when it had come to thermal equilibrium.
2. Immerse the sensing portion in a steam bath at 1 Standard atmosphere (101.325 kPa; 760.0 mmHg) and again mark the point indicated.
3. Divide the distance between these marks into equal portions according to the temperature scale being used.

Other fixed points were used in the past are the body temperature (of a healthy adult male) which was originally used by Fahrenheit as his upper fixed point (96 °F (36 °C) to be a number divisible by 12) and the lowest temperature given by a mixture of salt and ice, which was originally the definition of 0 °F (−18 °C).[25] (This is an example of a Frigorific mixture). As body temperature varies, the Fahrenheit scale was later changed to use an upper fixed point of boiling water at 212 °F (100 °C).[26]

These have now been replaced by the defining points in the International Temperature Scale of 1990, though in practice the melting point of water is more commonly used than its triple point, the latter being more difficult to manage and thus restricted to critical standard measurement. Nowadays manufacturers will often use a thermostat bath or solid block where the temperature is held constant relative to a calibrated thermometer. Other thermometers to be calibrated are put into the same bath or block and allowed to come to equilibrium, then the scale marked, or any deviation from the instrument scale recorded.[27] For many modern devices calibration will be stating some value to be used in processing an electronic signal to convert it to a temperature.

Mercury-in-glass thermometer

Precision, accuracy, and reproducibility

The **precision** or **resolution** of a thermometer is simply to what fraction of a degree it is possible to make a reading. For high temperature work it may only be possible to measure to the nearest 10°C or more. Clinical thermometers and many electronic thermometers are usually readable to 0.1°C. Special instruments can give readings to one thousandth of a degree. However, this precision does not mean the reading is true or accurate.

The "*Boyce MotoMeter*" radiator cap on a 1913 Car-Nation automobile, used to measure temperature of vapor in 1910s and 1920s cars.

Thermometers which are calibrated to known fixed points (e.g. 0 and 100°C) will be **accurate** (i.e. will give a true reading) at those points. Most thermometers are originally calibrated to a constant-volume gas thermometer. In between a process of interpolation is used, generally a linear one.[27] This may give significant differences between different types of thermometer at points far away from the fixed points. For example the expansion of mercury in a glass thermometer is slightly different from the change in resistance of a platinum resistance of the thermometer, so these will disagree slightly at around 50°C.[28] There may be other causes due to imperfections in the instrument, e.g. in a liquid-in-glass thermometer if the capillary varies in diameter.[28]

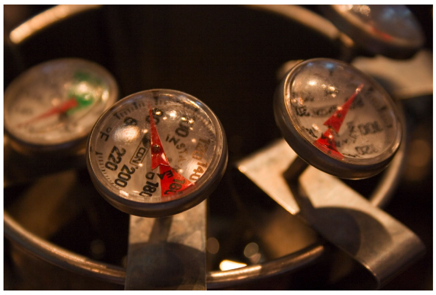
For many purposes **reproducibility** is important. That is, does the same thermometer give the same reading for the same temperature (or do replacement or multiple thermometers give the same reading)? Reproducible temperature measurement means that comparisons are valid in scientific experiments and industrial processes are consistent. Thus if the same type of thermometer is calibrated in the same way its readings will be valid even if it is slightly inaccurate compared to the absolute scale.

An example of a reference thermometer used to check others to industrial standards would be a platinum resistance thermometer with a digital display to 0.1°C (its precision) which has been calibrated at 5 points against national standards (−18, 0, 40, 70, 100°C) and which is certified to an accuracy of ±0.2°C.[29]

According to a British Standard, correctly calibrated, used and maintained liquid-in-glass thermometers can achieve a measurement uncertainty of ±0.01°C in the range 0 to 100°C, and a larger uncertainty outside this range: ±0.05°C up to 200 or down to −40°C, ±0.2°C up to 450 or down to −80°C.[30]

Uses

There are many and various uses for thermometers. Alcohol thermometers, infrared thermometers, mercury-in-glass thermometers, recording thermometers, thermistors, and Six's thermometers are used outside in areas which are well-exposed to the elements at various levels of the Earth's atmosphere and within the Earth's oceans is necessary within the fields of meteorology and climatology. Airplanes use thermometers and hygrometers to determine if atmospheric icing conditions exist along their flight path, and these measurements are used to initialize weather forecast models. Thermometers are used within roadways in cold weather climates to help determine if icing conditions exist and indoors within climate control systems. Thermometers are handy during cooking in order to know if meat has been properly cooked. Thermometers are used in the production of candy. Medical thermometers are used within health care to determine if individuals have a fever or are hypothermic. Liquid crystal thermometers can also be used to measure the temperature of water in fish tanks. Fiber Bragg grating temperature sensors are used within nuclear power facilities to monitor reactor core temperatures and avoid the possibility of nuclear meltdowns.


Bi-metallic stem thermometers used to measure the temperature of steamed milk

Thermometers have been built which utilize a range of physical effects to measure temperature. Temperature sensors are used in a wide variety of scientific and engineering applications, especially measurement systems. Temperature systems are primarily either electrical or mechanical, occasionally inseparable from the system which they control (as in the case of a mercury-in-glass thermometer). Alcohol thermometers, infrared thermometers, mercury-in-glass thermometers, recording thermometers, thermistors, and Six's thermometers are used outside in areas which are well-exposed to the elements at various levels of the Earth's atmosphere and within the Earth's oceans is necessary within the fields of meteorology and climatology. Airplanes use thermometers and hygrometers to determine if atmospheric icing conditions exist along their flight path, and these measurements are used to initialize weather forecast models. Thermometers are used within roadways in cold weather climates to help determine if icing conditions exist. Indoors, thermistors are used in climate control systems such as air conditioners, freezers, heaters, refrigerators, and water heaters.[31] Galileo thermometers are used to measure indoor air temperature, due to their limited measurement range.

Bi-metallic stemmed thermometers, thermocouples, infrared thermometers, and thermisters are handy during cooking in order to know if [meat has been properly cooked. Temperature of food is important because if it sits within environments with a temperature between 5 °C (41 °F) and 57 °C (135 °F) for four hours or more, bacteria can multiply leading to foodborne illnesses.[31] Thermometers are used in the production of candy. Medical thermometers such as mercury-in-glass thermometers,[32] infrared thermometers,[33] pill thermometers, and liquid crystal thermometers are used within health care to determine if individuals have a fever or are hypothermic. Liquid crystal thermometers can also be used to measure the temperature of water in fish tanks. Fiber Bragg grating temperature sensors are used within nuclear power facilities to monitor reactor core temperatures and avoid the possibility of nuclear meltdowns.[34]

Various types of thermometer

- Beckmann differential thermometer
- Bi-metal mechanical thermometer
- Coulomb blockade thermometer
- Galileo thermometer
- Resistance thermometer
- Reversing thermometer
- Silicon bandgap temperature sensor
- Six's thermometer
- Phosphor thermometry
- Alcohol thermometer

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