THERMOMETRY

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Thermometry is the science and practice of temperature measurement. Any measurable change in a thermometric probe (e.g. the dilatation of a liquid in a capillary tube, variation of the electrical resistance of a conductor, of the refractive index in a transparent material, and so on) can be used to mark temperature levels, that should later be calibrated against an internationally agreed unit if the measure is to be related to other thermodynamic variables (if the measure is only needed to establish an ordering in thermal levels, no calibration is required).

Thermometry is sometimes split in metrological studies in two subfields: contact thermometry and non-contact thermometry. Thermometers measure their own temperature, not that of the surroundings except if in thermal equilibrium. As there can never be complete thermal uniformity at large, thermometry is always associated to a heat transfer problem with some space-time coordinates of measurement, given rise to time-series plots and temperature maps (profiles, if one-dimensional).

Applications

Temperature is one of the most measured physical parameters in science and technology; typically for process thermal monitoring and control. But thermometry is not only applied to measuring temperatures for thermal control, but as an indirect measure of many material properties like thermal capacities and enthalpy changes (by thermal analysis), relative humidity (by means of wet bulb or dew-point temperatures), thermo-optical properties and other radiation characteristics (e.g. for the radiation budget of a planet), etc.

Ambient temperature in meteorology (also named air surface temperature) is measured using a thermometer under shelter from direct sun radiation, but well ventilated, placed some 1.5 m above clear ground. Climate records at Madrid can be found aside.

Temperature regulation in thermostatic baths, can be based on efficient thermal buffering (e.g. phase change devices), or on controlled heat transfer from a source or to a sink. A thermostat is a device that maintains a system at a constant temperature, issuing a control signal when out of limits. A common thermostat consists of a bimetallic strip that bends as it expands when overheating, switching of the electrical power supply.

Temperature regulation in mammals and birds (homoeothermic animals) is based on the hypothalamus (a neural control centre in the base of the brain also dealing with hunger, thirst, satiety, and other autonomic functions), where some neurons discharge at a rate proportional to absolute temperature, sending nerve signals and hormones to initiate shivering, sweating or panting, and controlling blood flow to limbs and skin to increase or decrease heat losses. In humans, the hypothalamus tries to regulate body temperature to 37±1 ºC under normal circumstances, but allows it to rise to 40 ºC during intensive exercise (to accelerate metabolism) and during infections (to better fight bacteria); there are even some dessert antelopes that allow their body temperature to rise to 45 ºC to save transpiration, while keeping their brains below 40 ºC by panting. Thermal comfort depends a lot on ambient temperature, wind and humidity, but also on subjects (e.g. clothing habits) and other interactions (type of activity, previous accommodation). An abnormally low body temperature, either naturally caused by a cold environment or by disease, or artificially performed to help in heart and brain surgery, is cold hypothermia.

Temperature metrology

Metrology is the science of measurement. Measuring is comparing a physical magnitude with an agreed unit from that magnitude. The result of measuring has three elements: the unit used, and the two multiples or divisions of the unit between which the sample sits; e.g. the mass of a given book is between 1.23 and 1.24 kg ('1.23', '1.24', and 'kg'); equivalently, the three elements may be: the unit, the best estimate value, and the uncertainty. However, it is customary to implicitly assume that the uncertainty is just half the value of the last significant digit quoted in the value, what is a handy practical simplification, but can be pedagogically misleading (how many university students give nonsense results like 1234.56789 K for an adiabatic combustion temperature, for instance).

The seven basic magnitudes in the SI of units are: time, length, mass, temperature, electrical intensity, luminous intensity and amount of substance, and all other magnitudes are defined in terms of those. But temperature is unique as being the only intensive magnitude from the seven. As measuring is comparing with multiples or submultiples of the unit adopted, it is most desirable that magnitudes be chosen extensive (or derived straight from extensive magnitudes), such that simple juxtaposition of the unit or division of it can furnish a system for direct comparison; e.g. a juxtaposition of several mass units can be used to compare with the mass a new-born baby to find that he/she is between 3 kg and 4 kg, for instance; or a juxtaposition of several beats of a pendulum beating seconds can be used to find his/her heart rate (nearly 2 s between beats); or a juxtaposition of metre-divisions (for instance in halves and quarters) can be used to measure his/her length (about two quarters of a metre). But a juxtaposition of two systems with the same temperature has not double temperature.

Temperature (officially 'thermodynamic temperature', to distinguish it from empirical thermal level gradations), according to the most recent international agreement on that (CGPM-13, 1967), has the unit 'kelvin', which is the fraction 1/273.16 of the temperature of the triple point of pure water (TPW), the primary standard, described below, but it is obvious that two such triple-point units do not have double temperature than a single unit. Only one fix point is needed because the other is taken at absolute zero value of temperature (before CGPM-10-1954, two fix points were adopted and the absolute zero was changing with state-of-the-art thermometry refinements). The International Organization for Standardization has issued a set of norms related to thermometry, the basic one being ISO 80000-5:2007 Quantities and units -- Part 5: Thermodynamics.

As unit-juxtaposition or division cannot be applied to temperature, not only the unit of a magnitude is needed, but a function of calibration for all other practical values, i.e. besides the TPW-cell (the unit), a universal thermometric procedure. So far (see ITS-90 below), several procedures are taken as primary, i.e. based on universal laws of thermodynamics, namely:

- The ideal-gas, constant-volume thermometer. For any real gas at low pressure (with T_{TPW}=273.16 K):

$$\frac{T}{T_{TPW}} \equiv \lim_{p \to 0} \frac{pV}{(pV)_{TPW}}$$

(1)

- The acoustic gas thermometer. For any real gas at low pressure, the sound speed is $c = \sqrt{\gamma RT}$ and thus:

$$\frac{T}{T_{TPW}} \equiv \lim_{p \to 0} \left(\frac{c}{c_{TPW}} \right)^{1/2}$$

(2)

- The spectral and total radiation thermometers. For total radiation exiting from a cavity (total radiant exitance in the black-body limit is $M=\sigma T^4$):

$$\frac{T}{T_{TPW}} \equiv \lim_{\varepsilon \to 1} \left(\frac{M}{M_{TPW}} \right)^{1/4}$$

(3)

- The electronic noise thermometer. In 2003, Lafe Spietz et. al. presented a new primary electronic thermometer which relates temperature to voltage-dependent electrical noise from a

tunnel junction (the form of this signal involves only the ratio of electronic charge to Boltzmann constant and the Fermi-Dirac statistic governing electrons in a metal). Electronic noise thermometry has been investigated since 1928 when Nyquist derived, and Johnson measured, the formula $S_I=4k_B T/R$ for the current spectral density S_I (in A^2/Hz) for a resistance R, but the signals involved are very small, particularly at low temperatures, and high-gain amplifiers must be used, making this method impractical (the shot noise of a tunnel junction, however, is based on direct voltage measurement and can easily be applied across several orders of temperature range.

It might be argued that if temperature is defined in terms of the internal energy and entropy of a system by $T\equiv\partial U/\partial S|_V$, the metrology problem should be similar to the measurement of speed in terms of length and time by $v\equiv\partial L/\partial t$, but directly measuring energy and entropy in a real system is yet an unsolved problem. Another possibility might be to define temperature in terms of some mechanical magnitude of degenerated systems (e.g. average kinetic energy, $<E_k>$, of a mono-atomic gas at low pressure: $T\equiv 2<E_k>/(3k_B)$), and accord an standard exactly-defined value for Boltzmann constant, k_B, as a substitute of the triple point of water unit. It should be noticed that temperature so defined cannot adopt negative values (absolute temperature), except in some degenerated local states with bounded entropy, of no practical use. Notice, however, that there is nothing special in the chosen calibration function (except that the above choice keeps to the tradition of temperature as 'hotness level' instead of 'coldness level', and the linear expansion approximation in early liquid-in-glass thermometers).

The use of primary ITS-90 thermometers to high accuracy is difficult and time-consuming and there exist secondary thermometers, such as the platinum resistance thermometer, whose reproducibility can be better by a factor of ten than that of any primary thermometer. The last international agreement, CGPM-18-1987, adopted the so called International Temperature Scale, ITS-90, which extends upwards from 0.65 K to the highest temperature measurable using an optical pyrometer. The scale is based on

1. A set of defining fixed points whose temperatures are agreed (Table 1).
2. Some specified methods of interpolating between them, namely:
   - the helium vapour-pressure equations from 0.65 K to 5 K,
   - interpolating constant-volume gas thermometers from 3 K to 24.5561 K,
   - platinum resistance thermometers from 13.8033 K to 1234.93 K and
   - Planck radiation law at higher temperatures.

Table 1. Fixed points adopted by ITS-90 for the calibration of secondary standard thermometers*.

T_{90} (K)	T_{90} (ºC)	Fixed Point
13.8033	-259.3467	e-Hydrogen triple point
17.035	-256.115	e-Hydrogen vapour pressure point near 33.3213 kPa
20.27	-252.88	e-Hydrogen vapour pressure point near 101.292 kPa
24.5561	-248.5939	Neon triple point
54.3584	-218.7916	Oxygen triple point
83.8058	-189.3442	Argon triple point
234.3156	-38.8344	Mercury triple point
273.16	0.010	Water triple point

302.9146	29.7646	Gallium melting point
429.7485	156.5985	Indium freezing point
505.078	231.928	Tin freezing point
692.677	419.527	Zinc freezing point
933.473	660.323	Aluminium freezing point
1234.93	961.78	Silver freezing point

*Besides those fix-points, the solidification point of p-nitrotoluene 324.6 K and naphthalene 353.4 K, are commonly used.

The primary standard: the TPW-cell

The primary standard for temperature measuring is the triple-point of water cell (TPW-cell, Fig. 1). Triple points of pure materials, and in particular the three-phase equilibrium between its solid, liquid and vapour phases, are fix points, i.e. the temperature (and pressure) in the triple interface is independent of ambient pressure (while the container resists) and of room temperature (while the three-phase equilibrium is not wiped out by heat transfer from the surroundings). The reason is that there are two independent thermodynamic relations amongst the two variables p and T: two Clapeyron equations of phase equilibrium).

A TPW-cell consists of a cylindrical borosilicate glass container with a re-entrant well wider than 10 mm in diameter, nearly filled with pure gas-free water under vacuum (condensed directly in the cell), and sealed. Often, a tubular glass extension at the top of the cells serves as a convenient handle for lifting and carrying the cell, as a hook for supporting it in an ice bath, and as an indicator of partial pressure of air in the cell (further details aside). If left alone, the TPW-cell attains ambient temperature.
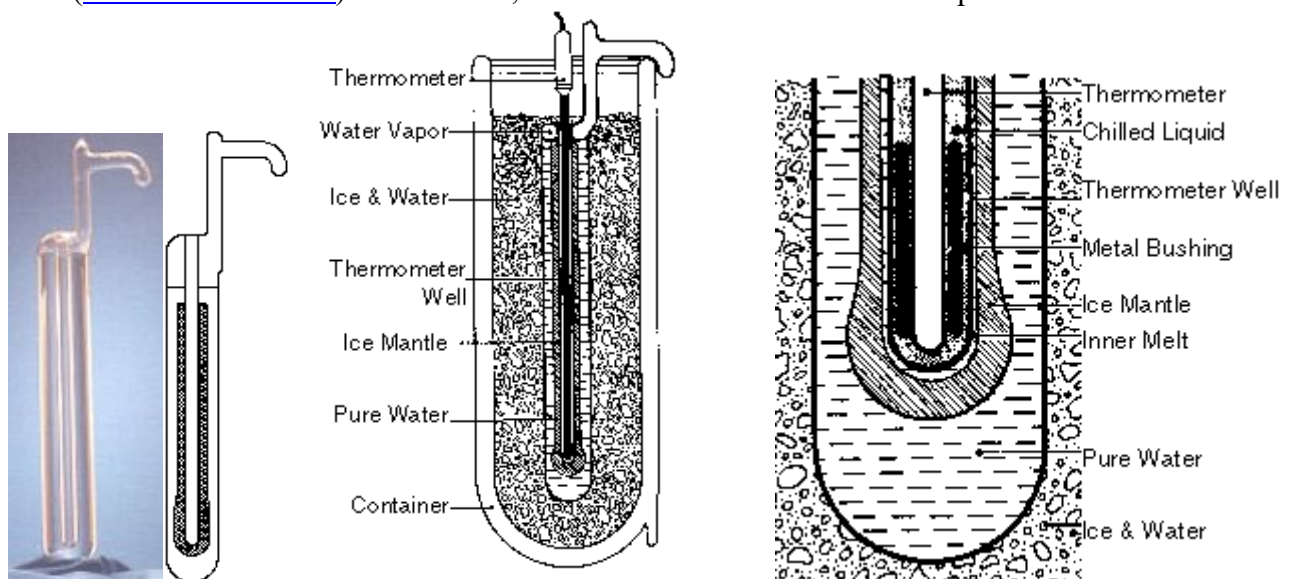

Fig. 1. Triple-point-of-water cell, with section and operational details.

To achieve the triple-point state, the cell is kept immersed in an ice-water bath to minimise thermal gradients (or in a thermoelectric controlled bath), and a freezing fluid mixture (e.g. some fine dry-ice chips) is put in the well to force growing an ice mantle around (a few millimetres thick, by viewing the cell from the bottom), without the ice going as far as the outer wall (the ice bridge expansion might brake the cell, some 1000 € worth for a certified cell). Afterwards, a thin layer of this ice mantle is melted next to the well by briefly inserting a rod of aluminium or glass at room temperature into the well, and the cell is ready to work, i.e. the triple point state is reached (for some while, while the ice ring is visible).

To check that no air was left inside the cell, with the cell initially upright (the well opening upward), the cell can be slowly invert until the axis passes through horizontal, and the water within the cell strikes the end of the cell, un-cushioned by air. At this point, a sharp clicking sound should be heard, resulting from the collapse of vapour bubbles.

The estimation of TPW-cell reproducibility, following standard construction rules, is in the range 100 μK to 10 μK, according to craftsmanship, i.e. better than 1 ppm ($10^{-4}/273$) or 273.1600±0.0001 K, the uncertainty being due to differences in water origin (isotopic composition), purification stages, vacuum achieved and cell closure details. Before CGPM-10-1954, the primary standard was the couple ice-point and boiling point, with a typical uncertainty of 0.01 K, i.e. 100 ppm ($10^{-2}/273$) or 273.15±0.01 K, the mayor uncertainty being due to impurities in the ice-water bath exposed to air. Ice baths are best made by mixing pure shaved ice (2..5 mm chips) and distilled water in an slender dewar flask (say less than 10 cm in diameter and more than 20 cm high).

The International Temperature Scale of 1990, a series of agreed temperature values, devices and procedures, is presently the best approximation to a magnitude that is consistent with all the known laws of thermodynamics.

Temperature and the ITS-90

The International Temperature Scale of 1990 (ITS-90) became the internationally recognized standard on January 1, 1990. The agreed primary thermometric procedures are:

- Between 0.65 K and 5 K, temperatures on the ITS-90 are defined in terms of the vapour-pressure temperature relations of ^{3}He and ^{4}He.
- Above 5 K, the ITS-90 assigns temperatures to sixteen fixed points (Table 1; the temperatures chosen are the best estimates of their thermodynamic temperatures). Between the fixed points, temperatures on the ITS-90 are obtained by interpolation using standard instruments and assigned formulae. These standard instruments are the helium gas thermometer (3 K to 24.5561 K), the platinum resistance thermometer (13.8033 K to 1234.93 K), and the optical thermometer (above 1234.93 K). Notice that there is some overlapping in the assigned ranges.

It should be remarked that the speed of sound of low pressure argon measured in a spherical acoustic resonator gives a very high accuracy from 1 K to 700 K.

The Celsius scale

Anders Celsius, Professor of Astronomy at Uppsala University, was the first (in 1742) to suggest a Centigrade Scale using 100 steps from the boiling point of water at 0, up to the freezing point of water at 100. It was Linneaus, the biologist, who used centigrade thermometers with the scale inverted in the form commonly used today.

The Celsius scale is defined after CGPM-10 of 1954 as a direct shift of absolute temperature values, namely:

$$T/^{o}C \equiv T/K - 273.15 \tag{4}$$

with the consequence that it is no longer centigrade by definition as before 1954. Present state of the art shows that the actual difference between the ice point and the steam point is 99.97±0.02 K (or ºC) at 1 atm (101325 Pa), and 99.60 ºC at the new standard of 100 kPa, but no longer 100, that is why it should no longer be called centigrade but Celsius scale. Note: although the international standards recommend the symbol t for temperatures in the Celsius scale, we use T for both, thermodynamic temperature (in kelvin) and Celsius temperature (in ºC), to avoid confusion with time t

Many other temperature scales were proposed in the past: Galen's 4-degrees of hot and 4-degrees of hotness, Newton's 12-degrees between ice point and human armpit point, Farenheit's 96-degrees between the ice-salt eutectic and human armpit point, etc.

Thermometers and thermal baths

Basically, a thermometer is a thermodynamic system small enough so that when thermally interacting (by contact or remotely) with the system under measure, the former gets thermalised with minimum impact on the latter. On the contrary, a thermal bath is a thermodynamic system big enough so that when thermally interacting (by contact or remotely) with the system under measure, the latter gets thermalised with minimum impact on the former. Any measurable change in the thermometer (e.g. the length of a capillary column, its electrical resistance, a resonant frequency, and so on) can be used to calibrate the thermometer against an internationally agreed unit.

The very first thermometer, Galileo's thermoscope, used air (water-trapped) as working fluid, but first practical thermometers used alcohol as working fluid. In 1641, Ferdinand II, the Grand Duke of Tuscany, had the first sealed thermometer constructed. This thermometer contained alcohol, with 50 marks on its stem but no fixed point. It became known as the "spirit thermometer". Over twenty years later, Robert Boyle in 1664 used red dye in his alcohol thermometer which included a scale from one fixed point: the freezing point of water. Boyle`s thermometer was used by the Royal Society in London until 1709. A thermometer with two fixed points, that of snow and boiling water, was developed by Ole Roemer in Sweden. Daniel G. Fahrenheit, in 1724, invented the mercury thermometer, with an accuracy unsurpassed until the 20th century.

A most important fact to keep in mind when measuring temperature is that hardly any real system is isothermal: liquid baths must be permanently stirred, gases are even more difficult to thermalise because of their poorer thermal conductivities, and thermal radiation from solids afar can contribute to the thermal balance of the probe. The basic role is 'always take redundant measures'.

Metrological properties

Metrology is the science of measurement. Metrology can be divided in the different physical fields, originally two, weights and (geometrical) measures, and nowadays nearly a dozen: time and frequency (which posed little problems because of the universal acceptance of the 'day' as natural unit), length (the

milestone here was the 1799-agreement to use decimal multiples and submultiples, not the metre itself), mass (the milestone here was the 1901-agreement to separate the meaning of mass and weight), temperature and heat (i.e. thermometry), electricity, photometry and radiometry, amount of substance (and composition specification), flow, acoustics, ionising radiation and radioactivity, etc. But there are some metrological properties common to all fields.

Several metrological characteristics determine the suitability of an instrument to a measurement problem, among them:

- Range is the interval of applicable temperatures, in kelvins or ºC. There are several possible ranges to consider; from shorter to wider, range of values for set precision, range of values for safe working (but not so accurate), range of values for storage, and range of values for irreversible damage.

- Sensitivity is the minimum change in a physical variable to which an instrument can respond. Sensitivity is often thought to coincide with resolution, which is the ability of an instrument to show up separate readings from closely different values of the variable being measured; i.e., the number of display figures in a digital instrument, or the smallest division in an analogue device. Although it is usually assumed that resolution gives a good estimate of accuracy, there may be no relation between them, the resolution being orders of magnitude finer than accuracy.

- Accuracy is the degree of conformity of a measured or calculated quantity to its nominal, or some other reference, value. The International Vocabulary of Basic and General Terms in Metrology (VIM) defines accuracy of measurement as "closeness of the agreement between the result of a measurement and a true value"; the VIM reminds us that accuracy is a "qualitative concept" and that a true value is indeterminate by nature.

- Uncertainty is the objective evaluation of accuracy. Uncertainty is often called error, in spite of the negative subjective implications of the latter. When all efforts have been taken to measure properly, the best value from a redundant set of measures is the arithmetic mean truncated to the accuracy corresponding to the standard deviation of the set, computed by:

$$\sigma \equiv \sqrt{\frac{\sum_{i=1}^{N}\left(x_i - <x>\right)^2}{N-1}} \ , \ <x> \equiv \frac{\sum_{i=1}^{N} x_i}{N} \tag{5}$$

  Additionally, the uncertainty to be assigned to a computation involving several different measures, $y=y(x_1, x_2...)$ is to be computed by:

$$\sigma_y \equiv \sqrt{\left(\frac{\partial y}{\partial x_1} \sigma_{x_1}\right)^2 + \left(\frac{\partial y}{\partial x_2} \sigma_{x_2}\right)^2 + ...} \tag{6}$$

- Traceability to higher accuracy standards. Traceability is the ability to accredit an unbroken chain of comparisons of actual measures to primary standards, by means of accredited laboratories, using calibrated instruments. Calibration is the actual tracing of one instrument to a higher standard in the traceability chain.

- Precision characterises the degree of mutual agreement among a series of individual measurements, values, or results, usually in terms of the deviation of a set of results from their arithmetic mean.

- Repeatability is the variation in a set of measurements arising when all efforts are made to keep conditions constant by using the same instrument, operator and procedures.
- Reproducibility is the variation arising using the same measurement process among different instruments and operators, and over longer time periods.
- Linearity is a desirable property to ease interpolation between calibrated measurements, but nowadays not so crucial if non-linearities are known (they can be corrected either in hardware or, more easily, by software).
- Sampling period is the time interval between observations. Sampling rate is limited by response time.
- Response time is the period required for the output of the instrument to rise to a specified percentage of its final value as a result of a step change in the input variable.
- Mechanical or other physical characteristics: size of sensor and auxiliary equipment, contact type (non-contact, surface contact, immersion), voltage and power required, set-up and warm-up time, material compatibility, strength, portability, handling skill level, etc.
- Economic and environmental aspects. Acquisition, operation and maintenance costs, environmental impact.

Types of thermometers

In the present computer age, thermometers may be grouped in electrical (i.e. which yield an electrical signal, like thermocouples and thermistors), and non-electrical (or mechanical, like mercury and bimetallic), which are seldom used in practice. We describe here the most used thermometers, starting with the old liquid-in-glass familiar type. There are also chromophoric substances (in the shape of sticker labels, pellets, crayons, liquid crystals, and so on), which change colour with temperature variations, either reversibly or irreversibly.

In information process diagrams, standard symbols and labels are used to represent different types of instruments and signal processing. Thermometers are tagged TT (temperature transducer), as pressure transducers are labelled PT, and fluid-flow meters FT.

Liquid-in-glass

Thermal expansion of a substance (solid, liquid or gas) can be used to measure temperature. The coefficient of thermal expansion is roughly $\alpha=10^{-5}$ 1/K for solids, 10^{-4} 1/K for liquids and 10^{-3} 1/K for gases. Bimetal thermometers are based on different expansion of solids, and constant-pressure gas thermometers may also be used. As gases are not easily handed, and solids do not expand so much, liquid-in-glass thermometers are the most common of the expansion type.

A typical liquid-expansion thermometer is shown in Fig. 2; some construction details follow. The bulb is not blown on the capillary tube itself, but is formed of a separate piece of tube fused on the stem. It is possible in this manner to secure greater uniformity of strength and regularity of dimensions. The thickness of the glass is generally between half a millimetre and one millimetre. The advantage shorter response time gained by making the glass thin is more than counterbalanced by increased fragility and liability to distortion. The best form of bulb is cylindrical, of the same external diameter as the stem, to

ease insertion through holes. The bore of the stem should also be cylindrical (and not oval or flattened), in order to diminish errors due to capillarity, and to secure the greatest possible uniformity of section. An example of analysis of design of such a thermometer can be seen in a separate Exercise.
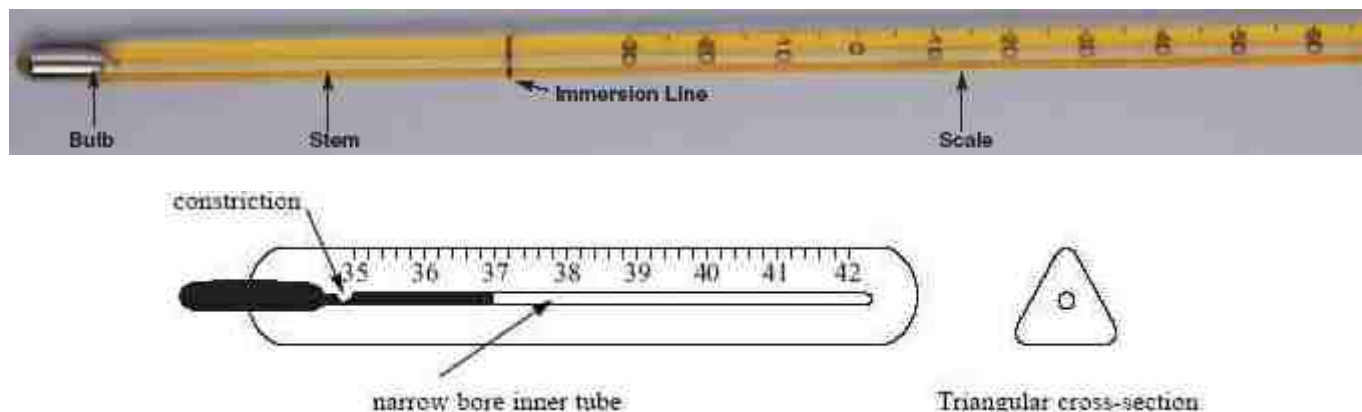

Fig. 2. A mercury-in-glass thermometer and details of a clinical thermometer.

Liquid-expansion thermometers are only used to measure temperature in fluids by immersion in them, totally or partially (what has an impact on calibration), but are useless to measure temperature in solids and surfaces. Mercury thermometers have been for the last 400 years the best choice in terms of economical accuracy, although nowadays environmental problems (see Mercury problems and alternatives), plus the trend to electronic automation, have relegated them to the museum.

Calibrations of dilatation thermometers are made by comparison with a standard platinum resistance thermometer in a constant temperature bath within the temperature range. Rough calibration with an ice bath and a boiling bath can yield uncertainties of a few tenths of a degree even after pressure corrections.

Thermocouple

A thermocouple is a couple of different conductors electrically connected at one end, the probe tip; between the open ends, a small electrical voltage appears that is proportional to the temperature difference between the joined tip and the open extreme, what is known as Seebeck effect. Thermocouples are the most common temperature sensing devices because of their wide temperature range, smallness, fast, response, toughness, simplicity and economy; provided there are no large thermal gradients along them, inexpensive compensating wires can replace nominal thermocouple conductors outside the sensitive region. Extension cables use the actual thermocouple materials, but in cheaper forms. This is achieved by using cheaper insulations, wider tolerance alloys and thinner conductors (as they will see little thermal stress in their lifetime). Semiconductor materials would yield larger gain than metals, but are too fragile for wires.

Some internal details of a thermocouple probe are shown in Fig. 3; PVC, silicon rubber or PTFE are common insulators up to 250 ºC, and glass fibre or ceramic is used above this. The protection sheath is often a metal alloy (or ceramic for high temperatures).
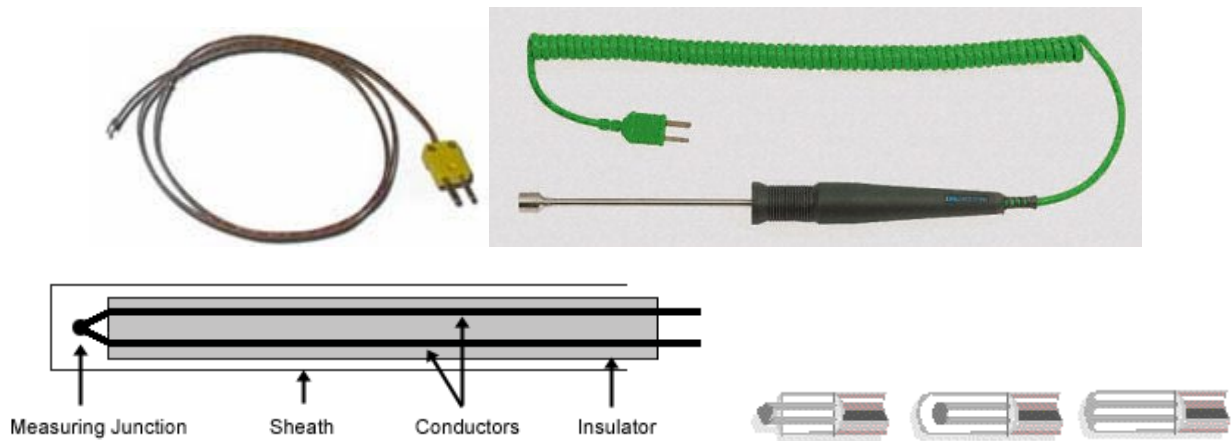
Fig. 3. Thermocouple with standard connector, surface probe with handle, internal sketch and the three different tip styles for a thermocouple.

Thermocouple output depends on the alloy mix of the conductors. No two mixes will be identical and sensor calibration is required if high accuracy is needed. The performance of an individual sensor will drift with high temperature exposure. Type K thermocouple is the most used, with one wire made of nickel-chromium alloy ('cromel') and the other of a nickel-aluminium alloy ('alumel'), yielding 40 µV/K of temperature difference. With proper sheath, K-thermocouples can measure from −200 ºC to 1300 ºC.

Thermocouples have the fastest response amongst contact thermometers (quantum radiometers can be faster), since micrometre-size wire gauges can be used; e.g. a response time of 2 ms is advertised for 25 µm diameter of bare wires, and there are thinner wires, but not strong enough for practical work). Fine thermocouples are used in hot-gas works to minimise the effect of thermal radiation from the walls, since the convective coefficient, $h=Nu·k/d$, becomes dominant in the thermal balance of the thermocouple bead, $mc\mathrm{d}T/\mathrm{d}t=hA(T_{\mathrm{gas}}-T)-\varepsilon A\sigma(T^4-T^4_{\mathrm{wall}})$, where d, m, c, T, A, and ε are the bead diameter, mass, thermal capacity, temperature, exposed area, and emissivity, respectively, and k is the fluid thermal conductivity (heat conduction along the wires is negligible with these thin gauges).

Platinum resistance (RTD)

Resistance Temperature Devices (RTD) are based on the change of the electrical resistance of a conductor with temperature. The electrical resistivity of metals can be approximated by $\rho=\rho_0(1+\alpha(T-T_0))$, with $\rho_0=0.017$ Ω·mm^2/m and $\alpha=0.0039$ 1/K for commercial copper, $\rho_0=0.068$ Ω·mm^2/m and $\alpha=0.007$ 1/K for nickel, $\rho_0=0.054$ Ω·mm^2/m and $\alpha=0.0045$ 1/K for wolfram, and $\rho_0=0.11$ Ω·mm^2/m and $\alpha=0.003850$ 1/K for platinum. Platinum is used in most instances because of its wide temperature range, accuracy, linearity, and stability; and Pt-100 probes in particular, where a coiled platinum wire wound around an insulator is used (typically the wire is about 0.05 mm in diameter and 2 m long, with a nominal resistance of 100 Ω at 0°C; the change is thus 0.385 Ω/K). Although no special extension cables or cold-junction compensation is required, RTD have to be powered to work (they are no passive devices like thermocouples), have a small gain, and lead wire resistance should be considered; a three or four wire connection strategy and a Wheatstone bridge are used to eliminate the connection lead resistance effects from measurements. Some internal details of a RTD probe are shown in Fig. 4.
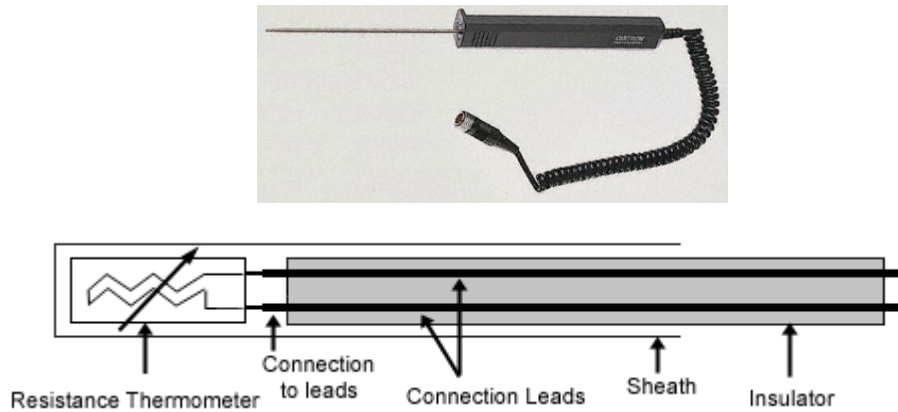
Fig. 4. Immersion probe and internal details of a RTD probe.

The standard platinum resistance thermometer (SPRT) defines the ITS-90 within the range 13.8033 K to 1234.93 K, when calibrated at specific sets of defining fixed points (Table 1 above), and used with specified reference and deviation functions for interpolation at intervening temperatures. Several differently constructed SPRT devices are used to cover the whole range.

Thermistors

Thermistors (THERMal resISTORS) are semiconductor materials with a rapidly changing electrical resistance with temperature. Contrary to metal conductors, which always show a positive temperature coefficient for resistivity (α in $\rho=\rho_0(1+\alpha(T-T_0))$), most thermistors show a Negative Temperature Coefficient (and are so named NTC-sensors), due to increasing number of electrons in conduction band with temperature (resistance is determined by the density of conduction electrons.). Typical NTC resistance characteristics are R=10 kΩ ($\pm$1%) at 25 ºC and dR/dT=$-$0.5 kΩ/K, instead of the typical RTD values R=100 Ω and dR/dT=0.385 Ω/K. There are also some Positive Temperature Coefficient thermistors (named PTC-sensors), mainly used in electric-current regulation, with a typical resistance of R=1 kΩ ($\pm$1%) at 25 ºC (they are made from doped ceramics or polymers). Thermistors are cheap and very sensitive, but they have a relatively narrow range, and require powering like for RTD.
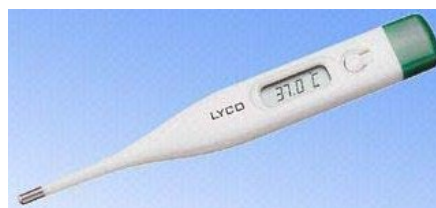

Fig. 5. An example of thermistor application: digital clinic thermometer.

Integrated Circuit temperature sensors (IC thermometer)

IC temperature sensors are semiconductor devices (two IC transistors coupled in saturated state), which produce an output current proportional to absolute temperature of the device when any voltage is applied (in the range 4..30 V DC). The device acts as a high impedance constant current regulator with typically 1 µA/K response (often set to 10 mV/ºC in the 0..100 ºC range with an internal or external circuit). They are cheap and insensible to electromagnetic noise in the basic current mode, but their operating range is very narrow ($-$50 ºC..150 ºC for goof linearity), size cannot be smaller than a few millimetres (low response time), and they require powering (what may increase its temperature up to 0.1 K).

Diode temperature sensors

Diodes can be used as a temperature measuring device, since the voltage difference between two p-n junctions, operated at different current densities (usually the same current and distinct junction area), is proportional to absolute temperature.

Silicon diode thermometers are most used in cryogenic applications. They have a constant negative thermal coefficient (NTC) of about −2 mV/K between 30 K and 400 K, which amounts to some −25 mV/K below 20 K. Accuracy may be ±0.5 K in the 2..100 K range.

Radiation thermometers and other non-contact thermometers

Non-contact thermometers may employ different physical phenomenon to determine temperature of the tested object: radiation phenomenon, refraction or phase Doppler phenomenon, luminescence phenomenon, Schlieren phenomenon etc. However, almost all systems used in practice for non-contact temperature measurement are based on the reception of thermal radiation from the object, and are termed radiation thermometers (RT). Non-contact temperature measurement is the preferred technique for small, moving, or inaccessible objects; dynamic processes that require fast response; and for high temperatures. Pyrometers are RT for work at high temperatures.

Radiation thermometers can be divided into a few groups according to different criteria: human role in the measurement, location of system spectral bands, presence of an additional cooperating source, number of system spectral bands, number of measurement points, width of system spectral bands and transmission media, etc. Their spectral band is constrained by good transmissivity through the intermediate media (ambient air in most cases), and minimum reflectance from other solids, thus, only portions of the IR spectrum are important, those atmospheric windows that provide maximum loss-free transmission through water vapour and carbon dioxide in air: the near-IR, 0.7..1.3 μm and 1.4..1.8 μm; the mid-IR, 2.0..2.5 μm, 3.2..4.3 μm and 4.8..5.3 μm; and the most used, the far-IR, 8..14 μm. The imaging optics must be transparent to IR radiation (e.g. germanium, which has τ=0,44 in the 2..15 μm range). There are two different types of detectors: thermal detectors and quantum detectors. The cheapest IR thermometers have a thermopile detector (i.e. a collection of thermocouples connected to each other in series in order to achieve better temperature sensitivity). IR thermometers have just one sensor, where the radiation from the object is concentrated; i.e. they are of spot or point type. A linear array of sensors, or a 1-D scanning optics can produce a 1-D temperature profile at once, but the most common and practical thermal imaging device is a 2-D array of sensors, or a 2-D scanning optics, or a 2-D sensor electronically scanned like a CCD, producing a temperature map of the region viewed at high sampling rate, i.e. thermal vision (of course, the images displayed can only represent temperature levels in a grey scale or a pseudo-colour arbitrary scale). Notice that IR thermometers measure the far-IR radiation that reaches them from the sample, i.e. the sum of what the sample emits plus what it reflects from the environment (for opaque samples in transparent environments), and, if the sample is at ambient temperature, this sum does not depend on the emissivity (e.g. the thermal image under these conditions is uniform and nothing can be seen).

Fig. 6. Ear IR-thermometer, 2-D array IR-unit, and handheld industrial IR-unit, and some internal details.

Table 4 presents a summary comparative of common thermometer types, and Fig. 7 a workbench for thermometric demonstrations.

Table 4. Comparison among common types of thermometers.

Characteristic	Thermocouple	RTD	Thermistor	Infrared
Range	−250..2600 °C	−200..850 °C	−60..300 °C	−50..3000 °C
Accuracy	Less Accurate	More Accurate	Less Accurate	Less Accurate
Size	Very small, 1 mm	Larger, 5 mm	Small, 1 mm	(non-contact)
Linearity	Quasi-Linear	Quasi-Linear	Not Linear	Quasi-Linear
Reference Junction	Required	Not Required	Not Required	Not Required
Lead Wire Resistance	No Problem	Must be Considered	No Problem	Not Required
Response	Fast	Slower	Medium	Fast

Fig. 6. An educational thermometric bench.

Temperature data acquisition

Data acquisition systems (DAQ) are automated systems (hardware and software) used to collect physical information of a real process, and to analyze it. DAQ equipment ranges from simple data indicators (e.g. a mercury thermometer) and recorders (a strip chart), to sophisticated computer systems with many sensors, some signal conditional electronic box, and PC-communication links. Data acquisition is a prerequisite to process control. Stand-alone DAQ systems have a microprocessor and memory to store the readings, and are usually called data-loggers. On-line DAQ systems use a PC to drive the process and store data (most data-loggers can connect online also), and to display in real time the processes in a graphical easy-to-understand form (by means of dedicated or general purpose DAQ programs).

Usually the sensor gives an analogue electrical output (e.g. voltage in thermocouples or intensity in integrated-circuit thermometers), and an analogue-to-digital conversion (ADC or A/D) stage must be

performed in the signal conditioner in a separate box like in the USB DAQ in Fig. 7, or assembled with the sensor (it used to be done in special plug-in cards at the PC).
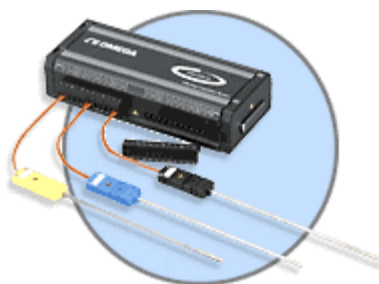

Fig. 7. A handy data acquisition module that connects several thermocouples (by means of detachable screw terminals) to a PC through a USB link (not shown).

Laboratory practice

How can students improve the most from their attendance to a thermal laboratory? The answer is hands on training in the use of equipment and, most important, practical experience in solving thermal problems. As a quick-check list we are using in our lab:

- Handle different type of thermometers to measure the temperature of: a) ambient air, b) boiling water, c) a cold solid (e.g. an aluminium block brought out from a fridge). It is common for first-time users to take a mercury-in-glass thermometer by the bulb.
- Compare the reading of several thermometers (of the same and different types). Note the different time response. Redundant measuring teaches more on metrological characteristics than the best theoretical explanation.
- Calibration. Let the student calibrate a thermistor, a thermocouple, or Galileo's thermoscope, with the ice and vapour points. Non-trained students tend to believe that water boils at 100.00 ºC.
- Thermal mapping. No system is at equilibrium; there are always gradients, some wanted and some unwanted. Use a set of thermocouples and a thermal-image camera to analyse twodimensional temperature fields like when heating a metal rod or plate from one side.
- Try some concrete application of thermometry. One example is to find out the visible efficiency of a light bulb, by gathering the thermal emission in a water bath whose temperature rise is measured (the whole emission can be found with a wattmeter or by absorption in water made opaque with black ink). A different example is to design and develop (there are IC chips to simply solve all electronic details) a thermostatic bath.

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