SIM
SISTEMA INTERAMERICANO DE METROLOGÍA

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METROLOGY
SCHOOL

Thermometry

SPEAKER

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Part 1

1.1 Metrology area domain

1.2 Historical evolution of temperature and its measurement scales

1.3 Measurement theory: measurement scales

Metrology area domain

- CCT = Consultative Committee for Thermometry. In fact, the CCT includes:

Field	Quantity (measurand)	Unit
Thermometry	Temperature, ***T***	- K or °C
Hygrometry (humidity and moisture)	Humidity: amount of water vapour in a gas: - Dew/frost point temperature, $\boldsymbol{t}_{\mathbf{D/F}}$ - Relative humidity, ***rh*** - Mole fraction of water, $\boldsymbol{x}_{\mathbf{W}}$ - Moisture: amount of water in materials	 - °C - % rh - $\text{mol}\cdot\text{mol}^{-1}$ - $\text{g}\cdot\text{Kg}^{-1}$
Thermophysical properties	- Emissivity, $\boldsymbol{\varepsilon}$ - thermal conductivity, ***k*** - thermal diffusivity, ***D*** - Thermal expansion coefficient, $\boldsymbol{\alpha}$	- (mW/nm)/(mW/nm) - $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ - $\text{m}^2\cdot\text{s}^{-1}$ - K^{-1}

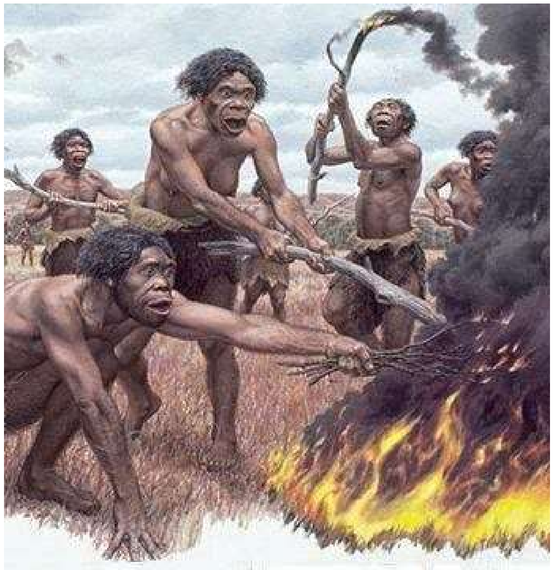
Historical evolution of temperature

- A short account of the most significant milestones in the historical development of the concept of temperature and its measurement scales

- Use a new tool, the modern “Measurement Theory,” to help identify these milestones and show:
  - How temperature evolved from a qualitative to a fully quantitative concept
  - How we gradually:
    - evolved our understanding of temperature and
    - encoded it in increasingly sophisticated measurement scales

The origin: the concepts of ‘hot’ and ‘cold’

- The concepts ‘hot’ and ‘cold’ originated during the earliest stages of human development:
  - 1.5 Mya: controlled use of fire by *Homo erectus*
  - 7500 ya: copper metallurgy (smelting)
  - 5500 ya: bronze metallurgy in the near East
  - 3200 BCE: the Hittites extracted iron from its ore into a workable metal
- None of these processes required a quantitative understanding of temperature and heat
- Only with the industrial revolution and the invention of the heat engine, the efficient use of heat demanded a better understanding of heat and temperature



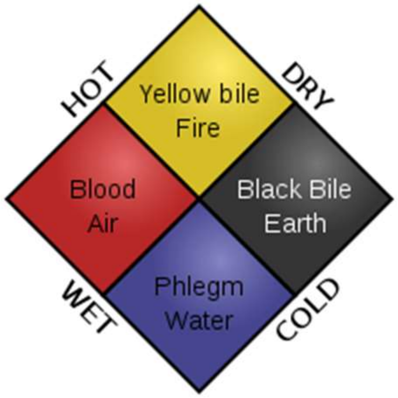
‘Hot’ and ‘cold’ as a measurement scale

Measurement theory (Stevens, 1946):

- With ‘hot’ and ‘cold’ you can already create a first simple type of measurement scale

- **Nominal Scale:** can only establish equality (can only say if two elements are equal or not)
  - Example: numbers on the uniforms of football players
    - Numbers are used as names, the actual number has no meaning
    - Number 10 is not two times larger (or better) than number 5

The word ‘*temperature*’: mixing the hot with the cold



- **Galen of Pergamon (129 - 210 CE):**
  - Health comes from a good mixing of contrary qualities: hot/cold and wet/dry
  - A person gets sick when there is imbalance between hot/cold and wet/dry
  - The goal of the physician is to find a remedy to the patient’s imbalance, so as to restore a **good balance (or good mix)**
- **The word ‘temperature’ appeared for the first time in the XVI century, when Galen’s works were translated into Latin by several authors:**
  - A noun form of the verb ***temperare*** (to temper) was introduced: ***temperatura***
  - The word ‘*temperature*’ meant tempering (moderating) something by mixing it with its contrary
  - For example, tempering the hot by mixing it with the cold
  - The word would have not been used for extreme heat, because extreme heat is not tempered by cold, so it is was a non-temperature (a *distemperature*)

The Galenic scale

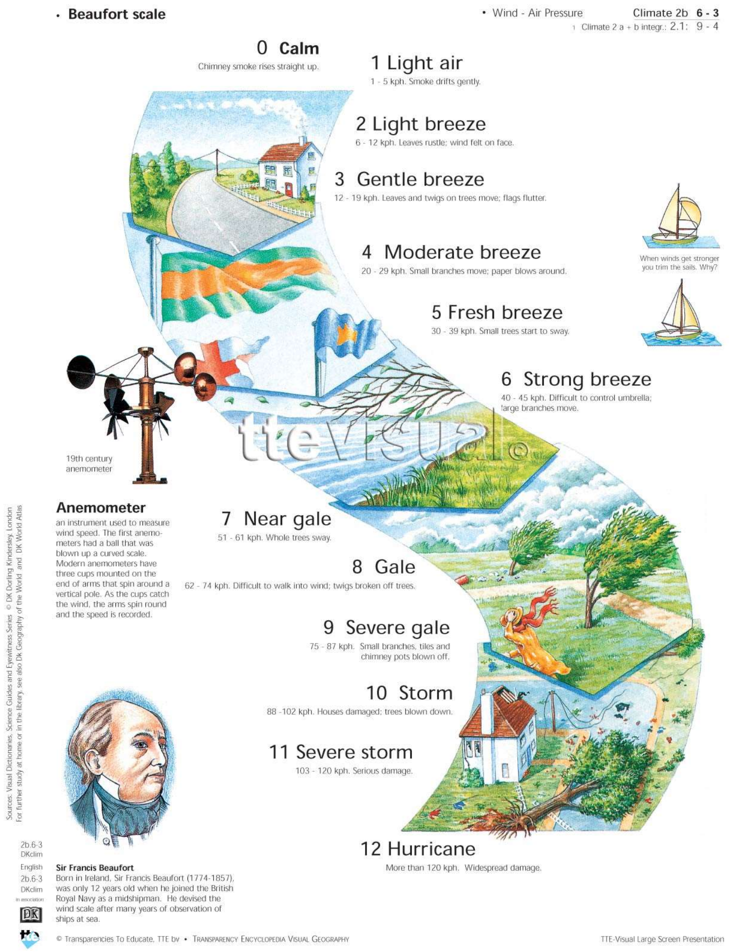
- XII – XVI century: Galenic physicians graded their patients on a nine-degree scale (Galenic scale):
  - The balanced mix (*bona temperatura*)
  - Four degrees hotter
  - Four degrees colder

extreme hot
severe hot
serious hot
moderate hot
“bona temperatura”
moderate cold
serious cold
severe cold
extreme cold

Ordinal scale

Measurement theory:

- Galenic scale is a second type of measurement scale: **ordinal scale**
- **Ordinal scale**: can establish equality and order
  - Not only $h_i = h_j$ or $h_i \neq h_j$
  - But also: $h_i > h_j$ or $h_i < h_j$
- **Example:** Beaufort wind-strength scale (13 grades)



Beaufort scale

Wind - Air Pressure

Climate 2b **6 - 3**

1 Climate 2 a + b integr.: 2.1: 9 - 4

0 **Calm**
Chimney smoke rises straight up.

1 Light air
1 - 5 kph. Smoke drifts gently.

2 Light breeze
6 - 12 kph. Leaves rustle; wind felt on face.

3 Gentle breeze
12 - 19 kph. Leaves and twigs on trees move; flags flutter.

4 Moderate breeze
20 - 29 kph. Small branches move; paper blows around.

5 Fresh breeze
30 - 39 kph. Small trees start to sway.

6 Strong breeze
40 - 45 kph. Difficult to control umbrella; large branches move.

7 Near gale
51 - 61 kph. Whole trees sway.

8 Gale
62 - 74 kph. Difficult to walk into wind; twigs broken off trees.

9 Severe gale
75 - 87 kph. Small branches, tiles and chimney pots blown off.

10 Storm
88 -102 kph. Houses damaged; trees blown down.

11 Severe storm
103 - 120 kph. Serious damage.

12 Hurricane
More than 120 kph. Widespread damage.

When winds get stronger you trim the sails. Why?

19th century anemometer

Anemometer
an instrument used to measure wind speed. The first anemometers had a ball that was blown up a curved scale. Modern anemometers have three cups mounted on the end of arms that spin around a vertical pole. As the cups catch the wind, the arms spin round and the speed is recorded.

Sir Francis Beaufort
Born in Ireland, Sir Francis Beaufort (1774-1857), was only 12 years old when he joined the British Royal Navy as a midshipman. He devised the wind scale after many years of observation of ships at sea.

Sources: Visual Dictionaries, Science Guides and Eyewitness Series © DK Dorling Kindersley, London
For further study at home or in the library, see also Dk Geography of the World and DK World Atlas

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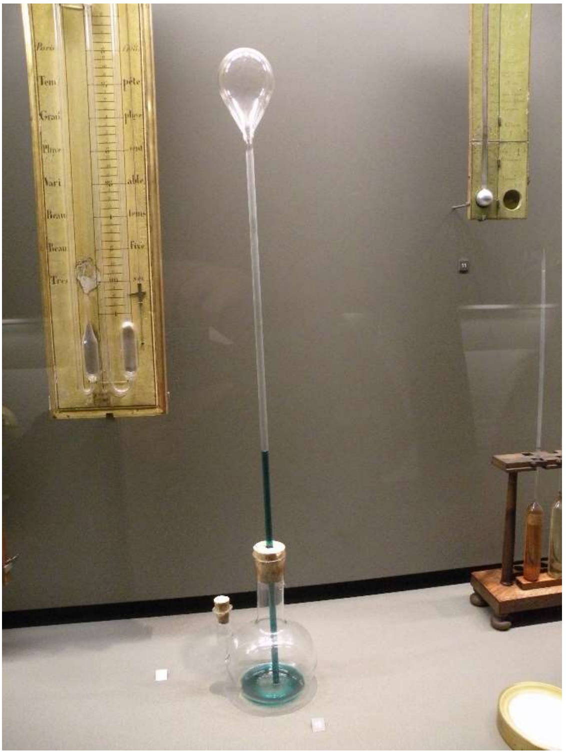
TTE-Visual Large Screen Presentation

Thermoscope

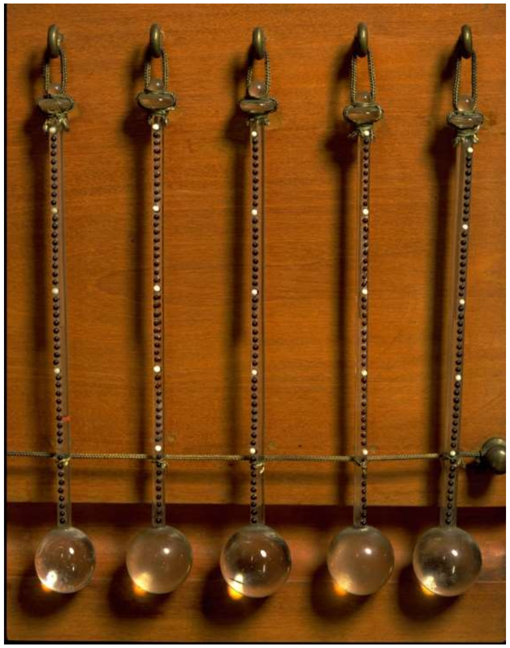
- **I – II century BCE:** Heron of Alexandria described a long-neck flask partly filled with water and inverted in water
  - The water in the tube rises as the enclosed air is cooled and falls as the air is heated
- **XVI century:** Heron's work was translated into Latin and became generally known to the natural philosophers of the epoch.
  - This is the precursor of any thermometer, although at that time nobody intended to use it as a thermometer (natural magic)
  - To distinguish it from the thermometer, we call it '**thermoscope**'
  - Still no quantitative scale (numbers were not assigned)
  - Correctly establish an order between different degrees of hot and cold
- Natural philosophers of the XVI century:
  - Understood that the thermoscope was able to order something
  - Did not understand what physical property it was ordering



Galileo's thermoscope, 1592
Musée des Arts et Métiers, Paris

The birth of the thermometer

- **XVII century:**
  - It became widely recognized that one could use the thermal expansion and contraction of **air** to measure variations in heat and cold
  - Closed devices using thermal expansion of a **liquid** instead of air were increasingly used:
    - First water replaced air to remove the influence of air pressure
    - Then alcohol replaced water because it was more sensitive and did not freeze
    - Finally mercury replaced alcohol because it was more reproducible
  - Still, across the whole XVII century, readings on thermometers were very erratic



Little Florentine thermometers by the Grand Duke of Tuscany, Ferdinand II de' Medici (1641): spirit-in-glass, scale marked with black and white glass bead, 50 ºG

Fahrenheit’s thermometers

- **1717:** Fahrenheit starts selling his mercury-in-glass thermometers in Amsterdam:
  - Thermometers started to behave consistently and agree with one another
  - Further evidence that thermometers were measuring some objective (but still unknown) property
  - People started to conceptualize temperature differently from their predecessors

- **1756:** Abbé Nollet in an article: “the temperature was 45 degrees on Fahrenheit’s thermometer”
  - Not anymore “the mercury in the thermometer rises and falls,” but “temperature rises and falls”

Daniel Gabriel Fahrenheit
(Gdańsk 1686 – The Hague 1736)

Empirical temperature scales

- **1724:** Fahrenheit introduced his mercury-based scale
  - Initially based on melting point of ice (32 ºF) and "*the degree of heat of a living man in good health*" (96 ºF)
  - He did not use the boiling point of water as a fixed point, but stated it as 212 ºF
  - Only after his death the boiling point replaced the blood heat as upper fixed point

- **1741:** Celsius introduced his mercury-based scale
  - Based on the freezing point of water (100 ºC) and the boiling point of water (0 ºC)
  - Why reversed?
    - If you think in terms of degree of cold, then the freezing point is a higher degree of cold than the boiling point

Daniel Gabriel Fahrenheit
(Gdańsk 1686 – The Hague 1736)

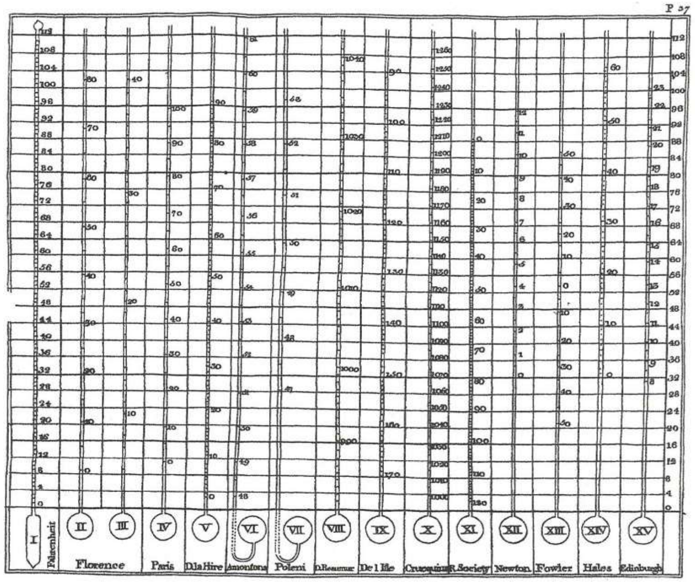
Anders Celsius
(Uppsala 1701 – 1744)

XVIII century: empirical temperature scales?

- XVIII-century empirical temperature scales are a significant development:
  - Now numbers are assigned
  - Increasingly well-thought and sophisticated

Measurement theory (Stevens' classification):

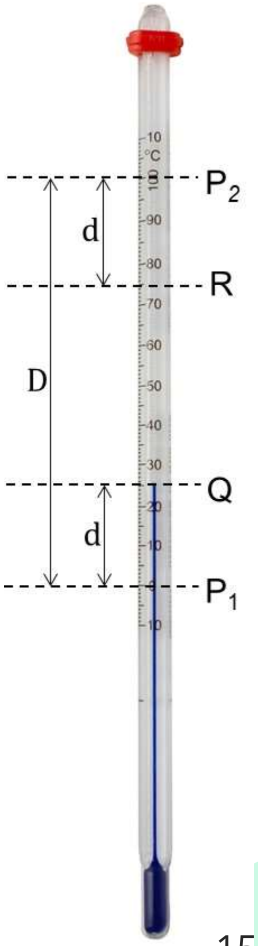
- Empirical scales of the XVIII century are ordinal scales
- **Ordinal scale:** can establish equality and order among "degrees of heat"
  - Not only: $h_i = h_j$ or $h_i \neq h_j$
  - But also: $h_i > h_j$ or $h_i < h_j$



Comparison of 15 temperature scales, 1772

Empirical temperature scales: the linearity dilemma

- Subtle problem:
  - Consider how the historical mercury-based Celsius scale is constructed:
    - Put a mark P_1 corresponding to ice point
    - Put a mark P_2 corresponding to steam point
    - Divide the interval $\overline{P_1 P_2} = D$ into 100 equal intervals
  - It assumes that mercury expands exactly and uniformly linearly in temperature
  - But how could that be established?
    - Need to know the function expressing the dependence of the volume of Hg on temperature
    - Such function could only be found with a thermometer whose non-arbitrariness had already been established



First half of XIX century:
Ok, we call it temperature, but what is it?

- Scientists believe in the existence of an objective property but facing challenging problems
- On one side, practical thermometry had achieved a good deal of reliability and precision
- On the other side, still a lot needed to be understood

Gay Lussac (1801): "*The thermometer, as it is at present constructed, cannot be applied to point out the exact proportion of heat, because we are not yet acquainted with the relation between its degrees and the quantities of heat*"

Thomson (1848): "*any existing scale is merely an arbitrarily series of numbered points of reference*"

Half of XIX century: the two big questions

- **What are thermometers measuring?**
  - What is the intrinsic (microscopic) physical property temperature refers to?
  - If you have two identical bodies which differ only in temperature, what is the physical (microscopic) difference between two?
  - What is changing (at microscopic level) in a body when its temperature changes?

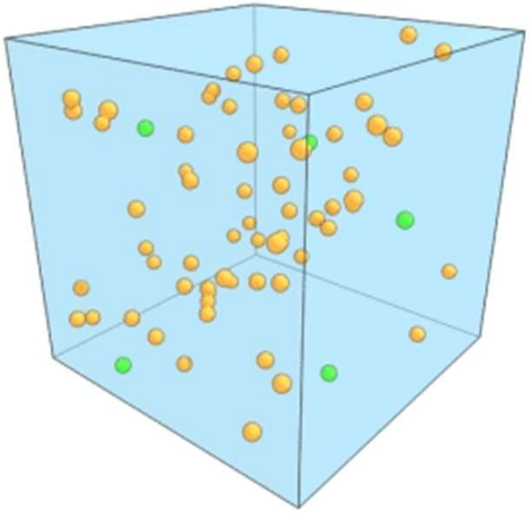
- **In what sense could a one-degree change at one temperature be the same as a one-degree change at another temperature?**

The answer to the first question

- **1857:** Clausius gave the answer to the 1st question
  - By that time the kinetic theory of heat had been widely accepted
  - Understood the microscopic meaning of temperature:
    - Temperature is proportional to the kinetic energy of the molecules that constitute a macroscopic body

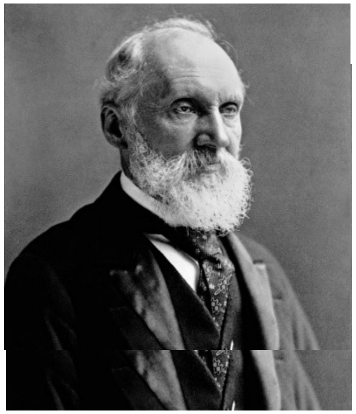
    - For an ideal gas of monoatomic non-interacting molecules at thermodynamic equilibrium:

$$\left\langle \frac{1}{2} m v^2 \right\rangle = \frac{3}{2} kT$$



- For the first time people understood what thermometers were measuring

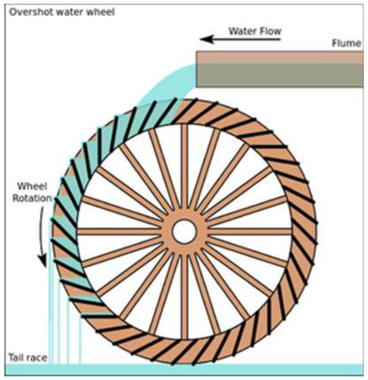
The answer to the second question



Sir William Thomson,
1st Baron Kelvin of Largs
(1824 - 1907)

- The answer to the 2nd question required much more conceptual thinking
- A connection between thermometry and the theory of heat was needed
- The connection was eventually made by William Thomson (Lord Kelvin):
  - Looking for an absolute scale: a scale that did not rely on a specific substance as the standard thermometric substance
  - Intrigued by the relation established by Carnot to express the mechanical work done by a heat engine (because it involved only quantities of heat and interval of temperatures)

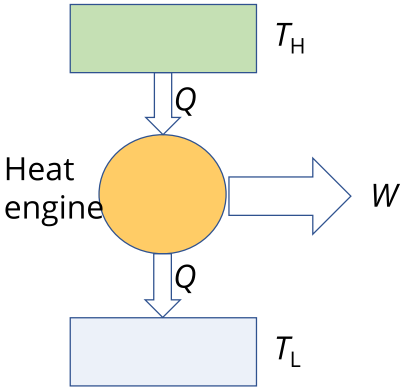
Thermodynamics: waterwheels and heat engines



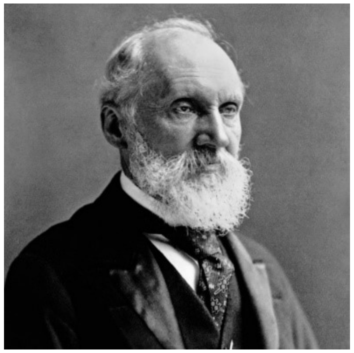
- **1824: Nicolas Leonard Sadi Carnot (1796 – 1832)**
  - Water enters a waterwheel at the top…
  - and **the same amount of water** exits at the bottom
  - In dropping from higher to lower, the water does mechanical work

- He thought of heat engines in the same way:
  - The engine does work by displacing heat from a place of higher temperature to a place of lower temperature

- He extracted the essence of functioning of all heat engines: **the mechanical work only depends on the temperature difference ΔT between the two thermostats**



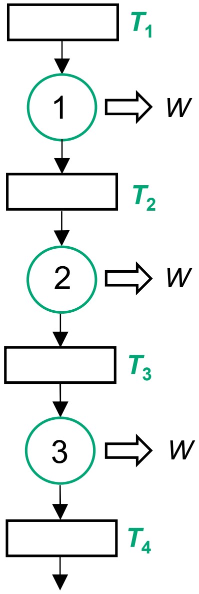
The answer to the second question (first attempt, 1848)



Sir William Thomson,
1st Baron Kelvin of Largs
(1824 - 1907)

- A cascade of Carnot engines, each producing the same mechanical work *W,* would operate between thermostats separated by the same temperature interval Δ*T*:

$$T_1 - T_2 = T_2 - T_3 = T_3 - T_4 = \cdots = \Delta T$$

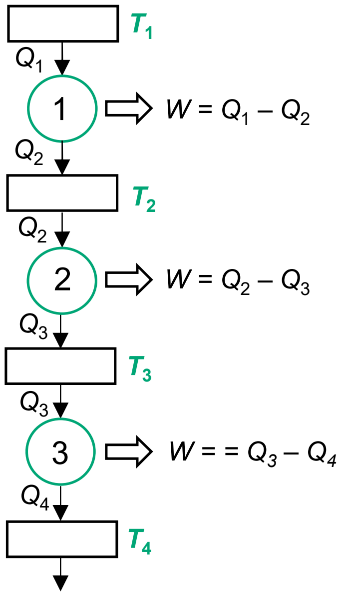


- **Each degree of temperature produces the same amount of mechanical work at any *T*** → Preserves equal intervals of hotness
- Absolute (independent from the physical properties of the working fluid)

Measurement theory:

- Thomson 1st proposal belongs to a 3rd type of measurement scale:
- **Interval scale** can establish:
  - Equality
  - Order
  - Equal intervals
  - Arbitrary zero

The answer to the second question (second attempt, 1854)

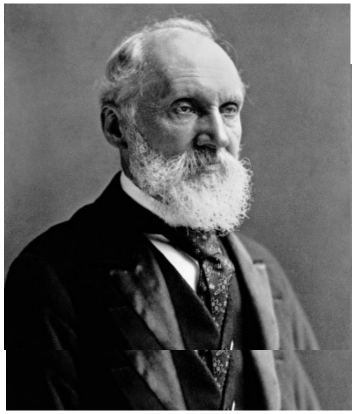


$$\boxed{\frac{Q_1}{T_1} = \frac{Q_2}{T_2} = \frac{Q_3}{T_3}}$$

- Thomson's proposal (1854): $\frac{\boldsymbol{Q_1}}{\boldsymbol{Q_2}} = \frac{\boldsymbol{T_1}}{\boldsymbol{T_2}}$
  - In a Carnot engine, the ratio of the two thermostat temperatures is equal to the ratio of the heats exchanged

Measurement theory:

- Thermodynamic temperature scale is a 4th type of measurement scale
- **Rational scale:**
  - Equality
  - Order
  - Equal Intervals
  - Equal ratios
  - Natural zero



Sir William Thomson,
1st Baron Kelvin of Largs
(1824 - 1907)

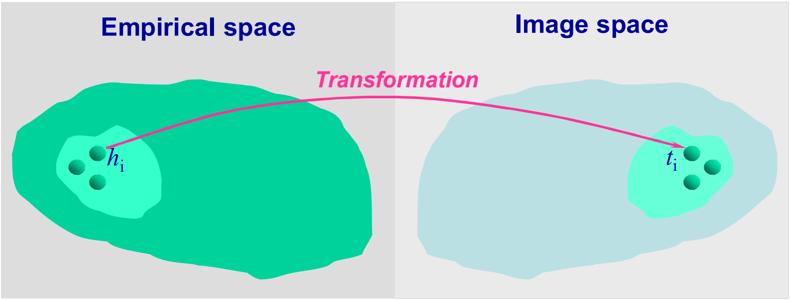
Measurement theory

- Over the centuries, the better we understood the nature of temperature, the better the temperature scales we devised were able to encode the structure of temperature in the numbers we used to measure it.
- This evolution took place mostly unconsciously and only in the past century we became aware of the mathematical structure and the properties of the different types of temperature scales we defined over the centuries (the same happened for the other SI quantities)
- Since more than one century, we have been speculating on:
  - How to define measurement
  - What sorts of things are measurable
  - Which conditions make measurement possible and meaningful
- This is the subject of **Measurement Theory**

Measurement theory

- **Representational Theory of Measurement (RTM)** (the most influential of the measurement theories):
  - A measurement scale is a correspondence between:
    - the space of the quantity/entity: h
    - the space of the numbers attributed to the quantity: $\mathbb{Q}$

$$f : h \rightarrow \mathbb{Q}$$



- **A measurement scale: assigns numbers to a quantity**
  - Relations exhibited by numbers (equality, difference, ratio, …) do not always correspond to meaningful relations among the quantities measured by those numbers

Type of measurement scales (Stevens, 1946)

Scale	Mathematical operations among numbers	Allowed scale transformations f: x → f(x)	Examples
Nominal	equality	f any 1:1 function	Uniform numbers in a football team
Ordinal	equality order	f any monotonic function	Celsius and Fahrenheit, Rockwell hardness
Interval	equality order equal intervals	$f: x \rightarrow ax + b$	Thomson scale (1848), latitude and longitude,
Rational	equality order equal intervals equal ratios	$f: x \rightarrow ax$	Kelvin thermodynamic scale, length, mass

- For each type of scale:
  - only specific **mathematical operations** are allowed among the numbers that express the quantities (see 2nd column)
  - Only specific **mathematical transformations** leave the scale undistorted (see 3rd column)

Type of measurement scales (Stevens, 1946)

Scale	Mathematical operations among numbers	Allowed scale transformations f: x → f(x)	Examples
Nominal	equality	f any 1:1 function	Uniform numbers in a football team
Ordinal	equality order	f any monotonic function	Historical Celsius and Fahrenheit, Rockwell hardness
Interval	equality order equal intervals	$f: x \rightarrow ax + b$	Thomson scale (1848), latitude and longitude,
Rational	equality order equal intervals equal ratios	$f: x \rightarrow ax$	Kelvin thermodynamic scale (1854), length, mass

➢ Scale operations with modern Celsius scale (interval scale)

- If we have 36 °C in Ottawa and 18 °C in Bogotá, does it make sense to say that temperature in Ottawa is twice that in Bogotá?

- If we have 19 °C in Bogotá, 10 °C in Moscow, 32 °C in Ottawa and 23 °C in Los Angeles, does it make sense to say that $T_{\text{Bogotá}} - T_{\text{Moscow}} = T_{\text{Ottawa}} - T_{\text{LosAngeles}}$?

Part 2

2.1 Thermodynamic temperature and primary thermometers

2.2 International Temperature Scale of 1990 (ITS-90):

- Fixed points, SPRTs and interpolation equations
- SPRT calibration and uncertainty budgets
- Non-uniqueness

2.3 $T - T_{90}$

Measuring thermodynamic temperature

- Primary thermometry methods (*Mise en pratique* for the definition of the kelvin in the SI, 2019, see Practical realizations - BIPM)*:*
  - Use a thermometer based on a well-understood physical system:
    - The equation of state, describing the relationship between T and other independent quantities, can be expressed explicitly without unknown or significantly temperature-dependent constants
    - Accurate measurement of the independent quantities
    - Sufficient understanding of the system to enable a quantitative assessment of non-ideality of the system in order to apply appropriate corrections

$$T = f(X, Y, Z, \ldots, \mathrm{A}, \mathrm{B}, \mathrm{C}, \ldots)$$

$X, Y, Z, \ldots$ measured independent quantities
$\mathrm{A}, \mathrm{B}, \mathrm{C}, \ldots$ known temperature-independent constants

Example: $PV = NRT$
P, V, N measured independent quantities
R known temperature-independent constant
Non-ideality: $PV = NRT\left(1 + B(T)\frac{N}{V} + C(T)\left(\frac{N}{V}\right)^2 + \cdots\right)$

Primary thermometry methods

- Primary thermometry methods currently included in the MePK:
  - Acoustic Gas thermometry (AGT)
  - Polarizing Gas Thermometry (PGT):
    - Dielectric Constant Gas Thermometry (DCGT)
    - Refractive Index Gas Thermometry (RIGT)
  - Johnson Noise Thermometry (JNT)
  - Radiometric thermometry (RT)

Acoustic gas thermometry (AGT)

(Range: 4 K to 552 K, best uncertainty: 1.8 ppm)

Review Article:
M.R. Moldover et al.
Acoustic gas thermometry
Metrologia **51** (2014) R1-R19

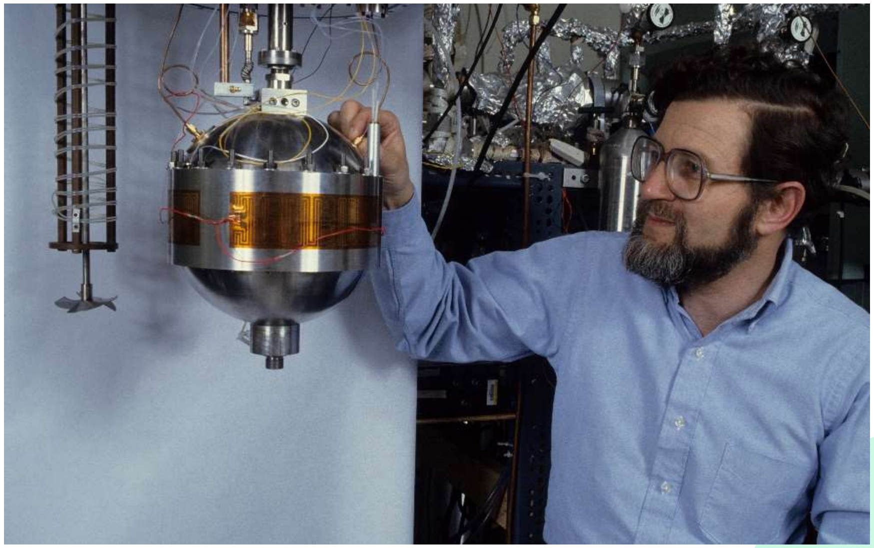
$$u^2 = \frac{\gamma_0 R T}{M}$$

$$(R = N_A k)$$

- Exploits the relationship between:
  - the speed of sound $\boldsymbol{u}$ in a dilute, monoatomic gas (He or Ar)
  - the thermodynamic temperature $\boldsymbol{T}$

$\boldsymbol{\gamma_0} = C_P^0 / C_V^0 = 5/3$
$\boldsymbol{M}$ = molar mass of the gas

- u is determined by measuring:
  - the acoustic resonance frequencies $\boldsymbol{f_a}$ of a gas-filled cavity (resonator)
  - The volume $\boldsymbol{V}$ of the resonator (often determined using microwave resonances)



Dielectric constant gas thermometry (DCGT)

(Range: 2.5 K to 273 K, best uncertainty: 1.9 ppm)

➢ Exploits electromagnetic properties of a gas described by the **Clausius-Mossotti equation:**

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{A_\varepsilon p}{RT}$$

- ε_r = relative dielectric constant (permittivity) ε_r
- A_ε = molar electric polarizability (QED *ab initio* calculations)
- p = pressure of the gas (measured)

- ε_r is measured by the change of the capacitance of a suitable capacitor enclosing the gas as the dielectric material

Review Article:
C. Gaiser et al.
Dielectric-constant gas thermometry
2015 *Metrologia* **52** S217

Refractive index gas thermometry (RIGT)

(Range: 5 K to 443 K, best uncertainty: 10 ppm)

- Exploits the optical properties of a gas described by the **Lorentz-Lorentz equation**:

$$\frac{n^2-1}{n^2+2}=\frac{(A_\varepsilon+A_\mu)p}{RT}$$

- $n^2 = \varepsilon_r \varepsilon_\mu$ refractive index
- A_ε = molar electric polarizability (QED *ab initio* calculations)
- A_μ = molar magnetic permeability (QED *ab initio* calculations)

- n is measured by detecting resonances of e.m. waves in a cavity resonator

Review Article:
P. Rourke et al.
Refractive-index gas thermometry
2019 *Metrologia* **56** 032001

Johnson noise thermometry (JNT)

(Range: 4 K to 1000 K, best uncertainty: 2.7 ppm)

Review Article:
SP Benz et al.
Practical realization of the kelvin by Johnson noise thermometry,
2024 *Metrologia* **61** 022001

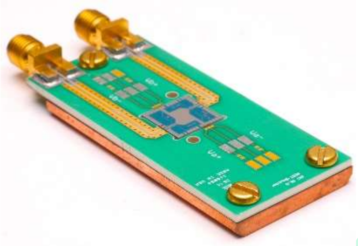
- Based on the electronic noise caused by the random thermal motion of the charge carriers within an electrical conductor **(Nyquist formula)**:
  - $\langle V^2 \rangle$ = mean square noise voltage
  - R = resistance of the resistor
  - Δf = bandwidth over which V is measured

$$\langle V^2 \rangle = 4kTR\Delta f$$

- **Relative primary noise thermometry:** Because the gain and bandwidth are difficult to quantify, usually two measurements are made, one with resistor R at the unknown T, and another with a reference noise source R_{ref} at a known temperature T_{ref}

$$T = T_{ref} \frac{\langle V^2 \rangle}{\langle V_{ref}^2 \rangle} \frac{R_{ref}}{R}$$

- **Absolute primary noise thermometry with QVNS:** the resistor providing the reference noise signal is replaced by a synthetic-noise source (QVNS).
  - **QVNS** = array of Josephson junctions, driven by a programmed sequence of pulses at a frequency of a few GHz, that produces a noise calculable in terms of quantum-based electrical standards (Benz 1999)



Thermodynamic temperature T and ITS-90 temperature T_{90}

- Thermodynamic temperature T is the fundamental quantity to which all temperature measurements should be related (traceable)

- For all practical purposes worldwide, practical international temperature scales have been periodically defined and used since 1927 (ITS-27, IPTS-48, IPTS-68 and ITS-90).

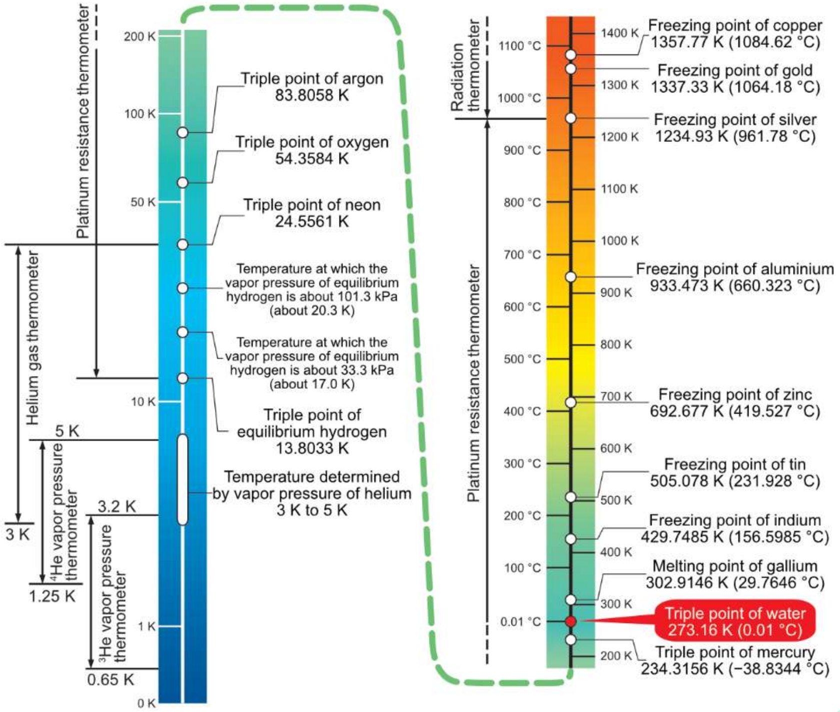
- Currently we use the temperature T_{90} on the International Temperature Scale of 1990 (ITS-90):
  - A proxy quantity for T
  - More easily realized and more reproducible than T

- There is another **defined scale** for ultra-low temperature: the PLTS-2000 from 0.9 mK to 1 K

The International Temperature Scale of 1990 (ITS-90)

- A protocol to realize a quantity (T_{90}) that is a close approximation to T.
- Introduces a number of temperature ranges
- For each temperature range, it specifies:
  - **The fixed points**
  - **The interpolating instrument (the type of thermometer)**
  - **The interpolating functions**

H. Preston-Thomas
The International Temperature Scale of 1990 (ITS-90)
Metrologia 27, 3-10 (1990)



The defining fixed points of the ITS-90

- Physical states of high-purity (better than 6N) substances:
  - Vapour-pressure point (vp)
  - Gas-thermometer point (gp)
  - Triple point (tp)
  - Melting point (mp) (at *P* = 101325 Pa)
  - Freezing point (fp) (at *P* = 101325 Pa)

- Numerical values reflect the knowledge of thermodynamic temperature in 1990.
- Realized using fixed-point cells
- Construction details are recommended in the *Guide to the Realization of the ITS-90* posted on the BIPM website.

See: https://www.bipm.org/en/committeees/cc/cct/guides-to-thermometry

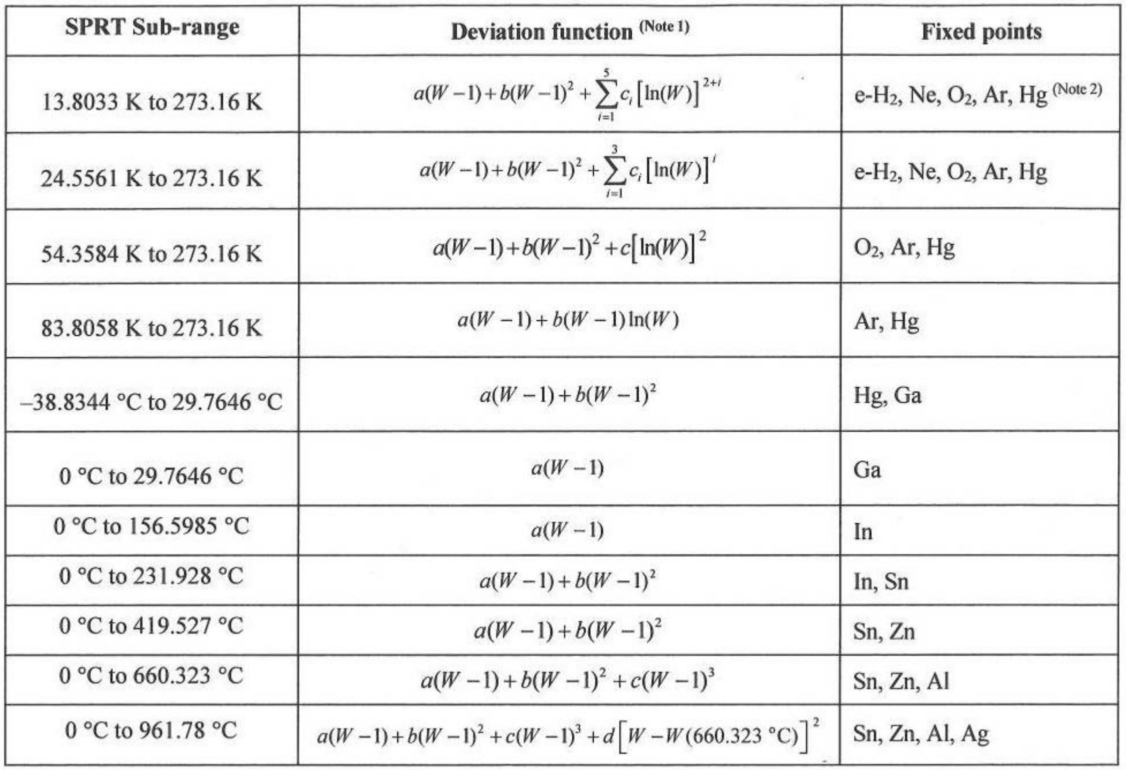
Substance	T /K	t_{90} /°C	State
He	3 to 5	-270 to -268	vp
e-H_2	13.8033	-259.3467	tp
e-H_2 or He	17.035	-256.115	vp or gp
e-H_2 or He	20.27	-252.88	vp or gp
Ne	24.5561	-248.5939	tp
O_2	54.3584	-218.7916	tp
Ar	83.8058	-189.3442	tp
Hg	234.3156	-38.8344	tp
H_2O	273.16	0.01	tp
Ga	302.9146	29.7646	mp
In	429.7485	156.5985	fp
Sn	505.078	231.928	fp
Zn	692.677	419.527	fp
Al	933.473	660.323	fp
Ag	1234.93	961.78	fp
Au	1337.33	1064.18	fp
Cu	1357.77	1084.62	fp

The interpolating instruments of the ITS-90

- From 0.65 K to 5 K: He vapour pressure thermometer (VPT)
- From 3 K to 24.5561 K: He interpolating constant-volume gas thermometer (ICVGT)
- From 13.8033 K to 961.78 °C: standard platinum resistance thermometer (SPRT)
- $T_{90} \geq 961.78$ °C: radiation thermometer (RT)

The interpolating functions for the SPRT range

- Further partition into 11 overlapping sub-ranges:
  - Provide flexibility
  - Introduce non-uniqueness where 2 or more subranges overlap



SPRT Sub-range	Deviation function (Note 1)	Fixed points
13.8033 K to 273.16 K	$a(W-1)+b(W-1)^2+\sum_{i=1}^{5} c_i\left[\ln(W)\right]^{2+i}$	e-H_2, Ne, O_2, Ar, Hg (Note 2)
24.5561 K to 273.16 K	$a(W-1)+b(W-1)^2+\sum_{i=1}^{3} c_i\left[\ln(W)\right]^{i}$	e-H_2, Ne, O_2, Ar, Hg
54.3584 K to 273.16 K	$a(W-1)+b(W-1)^2+c\left[\ln(W)\right]^2$	O_2, Ar, Hg
83.8058 K to 273.16 K	$a(W-1)+b(W-1)\ln(W)$	Ar, Hg
−38.8344 °C to 29.7646 °C	$a(W-1)+b(W-1)^2$	Hg, Ga
0 °C to 29.7646 °C	$a(W-1)$	Ga
0 °C to 156.5985 °C	$a(W-1)$	In
0 °C to 231.928 °C	$a(W-1)+b(W-1)^2$	In, Sn
0 °C to 419.527 °C	$a(W-1)+b(W-1)^2$	Sn, Zn
0 °C to 660.323 °C	$a(W-1)+b(W-1)^2+c(W-1)^3$	Sn, Zn, Al
0 °C to 961.78 °C	$a(W-1)+b(W-1)^2+c(W-1)^3+d\left[W-W(660.323\ ^\circ\mathrm{C})\right]^2$	Sn, Zn, Al, Ag

The Guide to the Realization of the ITS-90

- Describes methods by which the ITS-90 can be realized successfully
- Posted on the BIPM website
- Its parts have been written as self-contained papers by different authors
- Not prescriptive (only the text of the ITS-90 is prescriptive):
  - Recommends methods and techniques
- Evolving continuously

Guide to the Realization of the ITS-90

- Part 1 – Introduction (2018)
- Part 2.1 – Fixed points: Influence of impurities (2018)
- Part 2.2 – Triple point of water (2018)
- Part 2.3 – Cryogenic fixed points (2018)
- Part 2.4 – Metal fixed points for contact thermometry (2021)
- Part 2.5 – Fixed points for radiation thermometry (2018)
- Part 3 – Vapour pressure scales and pressure measurements (2018)
- Part 4 – Gas thermometry
- Part 5 – Platinum resistance thermometry (2021)
- Part 6 – Radiation thermometry (2018)

See:
https://www.bipm.org/en/committeees/cc/cct/guides-to-thermometry

The SPRT range of the ITS-90: Generalities

- In the range [13.8033 K, 1234.93 K] the interpolating instrument to be used is a platinum resistance thermometer that satisfies specified qualification criteria (related to the purity and the absence of strain of the platinum wire in the SPRT).
- Temperature-dependent physical quantity: electrical resistance $R(T_{90})$ of the SPRT
- Normalized by taking the resistance ratio:

$$W(T_{90}) = \frac{R(T_{90})}{R(T_{90} = 273.16K)} = \frac{R(T_{90})}{R_{TPW}}$$

Why introduce $W\ (T_{90})$ instead of using $R(T_{90})$?

- Depends only on the resistivity and on the thermal expansion of high-purity Pt → allows interpolations to be made with respect to differences from a generic reference function:

$$W(T_{90}) = \frac{R(T_{90})}{R_{TPW}}$$

$$W\ (T_{90}) = W_r(T_{90}) + \Delta W\ (T_{90})$$

Expresses the characteristics of a chosen high-quality SPRT (**fixed**)

Takes into account the peculiarities of each individual SPRT (different crystal orientations and grain size, different impurity concentrations, surface oxidation effects, vacancy effects, …) (**Determined by calibration**)

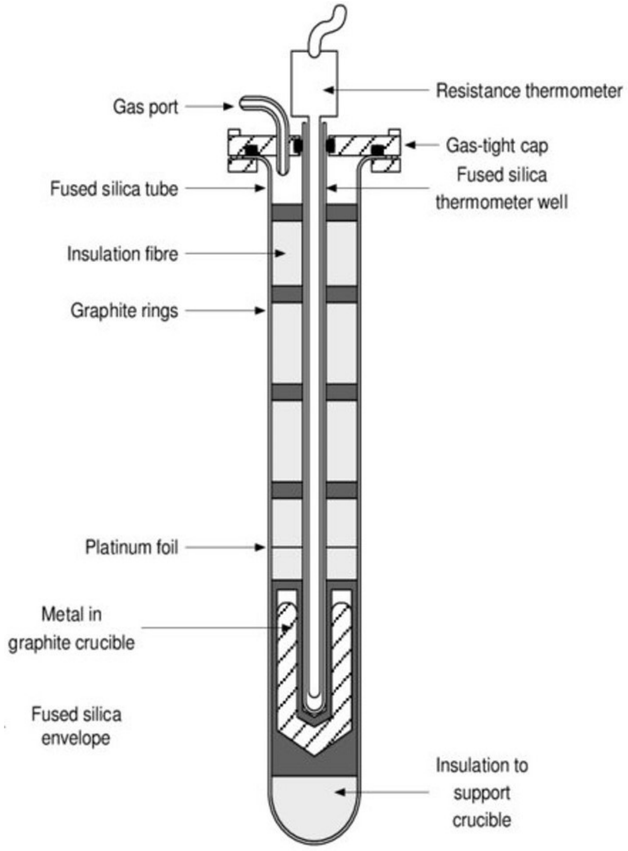
- Removes the need for traceability to absolute resistance standards:

$$W\ (T_{90}) = \frac{R(T_{90})}{R_{TPW}} = \frac{X(T_{90})\cdot \cancel{R_S}}{X_{TPW}\cdot \cancel{R_S}} = \frac{X(T_{90})}{X_{TPW}}$$

- Compensates for some SPRT instabilities (at least for temperature-independent resistance changes)

Metal fixed-point cells

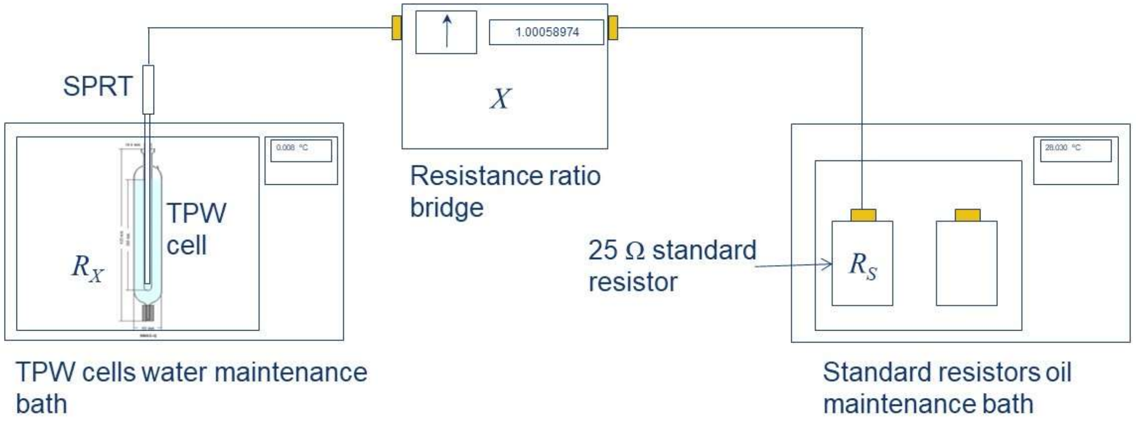
- High-purity (better than 6N) metal ingots
- Contained in a cylindrical high-purity high-density graphite crucible (SS or glass for Hg, Teflon for Ga)
- Re-entrant well in the graphite crucible to insert the SPRT
- Crucible contained in a Borosilicate or fused silica tube (including the thermometer well)



Calibration of an SPRT at an ITS-90 fixed point

- **Measurand:** the resistance of the SPRT when the SPRT is in thermodynamic equilibrium with the solid-liquid interface of the fixed-point cell
- **Measurement principle:** measure the ratio X (pure number) between the unknown SPRT resistance R_X and the known resistance R_S of a standard resistor
- X is measured with a resistance ratio bridge (best uncertainty: 20 ppb)

- $X = R_X / R_S$
- $R_X = X \cdot R_S$



Uncertainty budget for the measurement of an SPRT resistance at an ITS-90 fixed point

- Uncertainty sources associated to the fixed point realization:
  - Hydrostatic head correction
  - Gas pressure correction
  - Impurities
  - Isotopic composition
  - Strain, crystal defects
  - Thermal effects (SPRT sensing element not in direct contact with the solid/liquid interface)
  - Extrapolation to the liquidus point
- Uncertainty sources associated to the resistance measurement:
  - Reference resistor
  - Resistance ratio bridge
  - Self-heating
  - Connecting cables and lead resistances
- Uncertainty sources associated to the use of the SPRT:
  - Oxidation
  - Strain, vacancies, defects, contamination, moisture
  - Insulation leakage

Four different uncertainty budgets

- Evaluate the uncertainty in:
  1. The measurement of the resistance R_i of an SPRT at an ITS-90 fixed point i (e.g. R_{Zn})
  2. The measurement of the resistance ratio $W_i = R_i/R_{TPW}$ of an SPRT at an ITS-90 fixed point point i (e.g.$W_{Zn} = R_{Zn}/R_{TPW}$)
  3. The calibration of an SPRT in a given ITS-90 sub-range (e.g. in [TPW, Al]) → **Propagation of uncertainty (PoU):** need to calculate how the uncertainties in the measurement of the SPRT resistance ratios at the fixed points propagate to all other temperatures of the sub-range
  4. The use of a calibrated SPRT to measure T_{90}
- They are four different problems:
  - To solve one of them, you need to have preliminarily solved the previous ones

Non-uniqueness of the ITS-90

- Non-uniqueness arises because the ITS-90 is an **interpolated scale**. The interpolation is based on:
  - The definition of a reference function $W_r(T_{90})$
  - The definition of a deviation (interpolation) function $\Delta W(W)$ for each subrange

- Interpolation functions of the ITS-90:
  - Polynomials (above 0 °C)
  - Logarithmic powers (below 273.16 K)

- These simple functional forms of the interpolation functions are insufficient to characterize the many complex and poorly understood physical effects (crystal orientation, grain sizes, impurities, surface oxidation effects, vacancies, …) that make up the real $W(T_{90})$ characteristic of a real SPRT

- The interpolation functions are subject to interpolation error

- The interpolation error manifests itself in 3 types of non-uniqueness

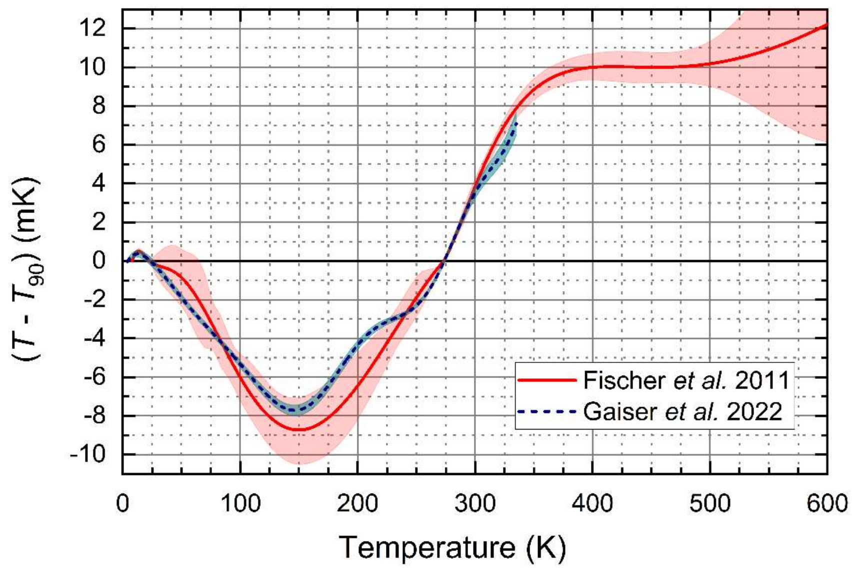
The three types of non-uniqueness

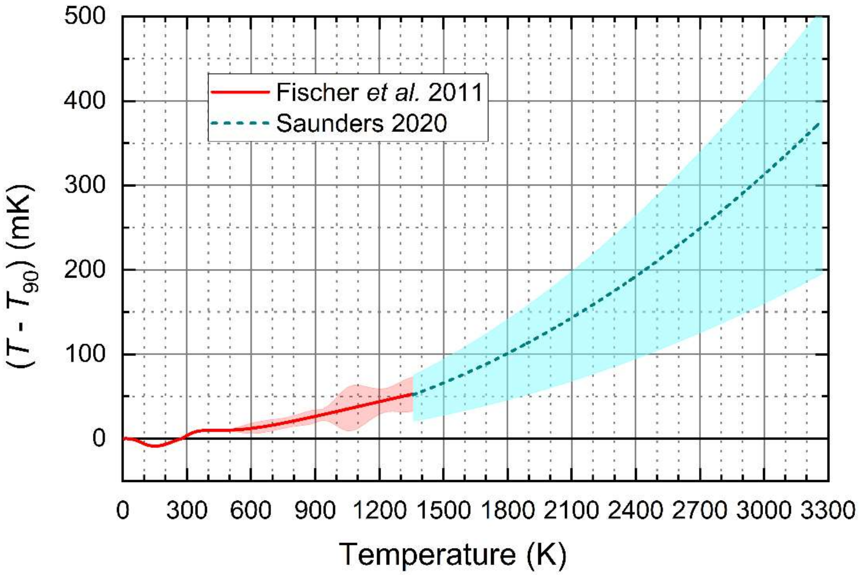
- **Type 1 NU** (also called sub-range inconsistency, **SRI**):
  - Arises from the fact that the ITS-90 allows SPRTs to be calibrated over different overlapping sub-ranges (more than one interpolation function)
  - The same SPRT will give different T_{90} values depending on which sub-range is chosen

- **Type 2 NU:**
  - Arises from the use of different kinds of thermometers in overlapping ranges (more than one type of interpolating instrument)

- **Type 3 NU:**
  - Arises because every SPRT has a slightly different characteristic from any other SPRT
  - Different SPRTs, calibrated in the same sub-range and against the same set of fixed points, return different values of T_{90} when compared at temperatures in between the fixed points

Thermodynamic inaccuracy of the ITS-90: $T - T_{90}$





P.M.C. Rourke, Future of the International Temperature Scale in a Mixed Dissemination Environment, *ITS10* (2024)

Thermodynamic inaccuracy of the ITS-90: $T - T_{90}$

Fixed Point	T_{90} /K	$u(T_{90})$ /mK (NRC)	$T - T_{90}$ /mK	$u(T - T_{90})$ / mK
Ar	83.8058	0.15	**-4.21**	0.15
Hg	234.3156	0.10	**-2.89**	0.13
TPW	273.16	0.05	**0.00**	0.10
Ga	302.9146	0.15	**3.84**	0.34
In	429.7485	0.15	**10.1**	0.8
Sn	505.078	0.35	**11.5**	1.3
Zn	692.677	0.30	**13.8**	6.9
Al	933.473	0.5	**28.7**	6.6
Ag	1234.93	2.5	**46.2**	14

Note that:

- $T - T_{90}$ is 20 to 70 times worse than $u(T_{90})$
- $T - T_{90}$ is 10 times worse than $u(T)$ up to In (for the best primary thermometry T realization)

$$(T - T_{90})\Big/\mathrm{mK} = \sum_{i=0}^{12} a_i (T_{90}/\mathrm{mK})^i$$

$$u(T - T_{90})\Big/\mathrm{mK} = \sum_{i=0}^{6} b_i (T_{90}/\mathrm{mK})^i$$

C. Gaiser *et al.*, 2022 update for the differences between thermodynamic temperature and ITS-90 below 335 K, *J. Phys. Ref. Data* 51, 043105 (2022)

Part 3

The redefinition of the kelvin

- From 1954 to 2019, the unit of thermodynamic temperature, the kelvin, was defined as *“the fraction* $1/273.16$ *of the thermodynamic temperature of the triple point of water”*

$$1\ K = \frac{1}{273.16} \cdot T_{\mathrm{TPW}}$$

- The kelvin was defined by assigning a numerical value of 273.16 K to the thermodynamic temperature of the triple point of water (TPW)

- We did not realize 1 K, we realized 273.16 K

- Any temperature measurement was an indirect comparison of the temperature to be measured with the temperature of the TPW

The triple point of water

- The unique physical state of water in which all three phases (solid, liquid, and vapour) coexist at thermodynamic equilibrium

- Realized in practice with a TPW cell:
  - A sealed fused-silica bottle containing about 0.5 litres of high-purity VSMOW water
  - A fraction of the water in the cell is frozen by cooling
  - The cell is accommodated in a water bath controlled at a temperature close to 273.16 K
  - Inside the bottle, the equilibrium between the 3 phases is spontaneously established
  - Can be maintained for several months

The old definition of the kelvin

- Linked to its practical realization with a *quasi-artifact* (the TPW cell)

- Differently from the old definition of the kilogram, it was not linked to a specific artifact: any laboratory could realize the kelvin by manufacturing its own TPW cell

- Uncertainty in $T_{\mathrm{TPW}} = 273.16$ K:
    - No thermodynamic uncertainty
    - Only uncertainty associated to its practical realization: ≈ 10 μK (for example, the water cannot be perfectly pure and exactly VSMOW)

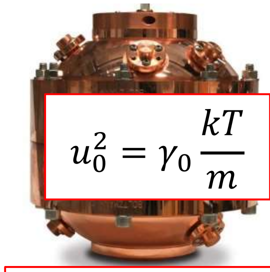
The Boltzmann constant *k* in the old SI

- *k* was a measured quantity: it has been measured very accurately in the first 20 years of this century with different primary methods:
  - AGT: measure the speed of sound of an ideal gas at the TPW
  - DCGT: measure the dielectric constant of an ideal gas at the TPW
  - JNT: measure the mean-square noise voltage across a resistor at the TPW

- CODATA 2017 Special Adjustment of fundamental constants:

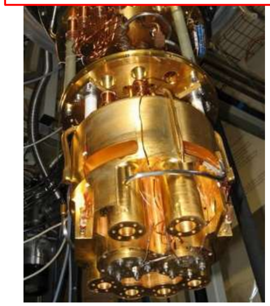
  k = 1.38064903·10^{-23} JK^{-1}
  u_r = 3.7·10^{-7}

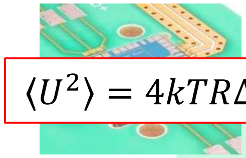
PJ Mohr et al., Data and analysis for the CODATA special fundamental constants adjustment, *Metrologia* **55** (2018) 125-148



$$u_0^2 = \gamma_0 \frac{kT}{m}$$

$$P = kT\frac{\varepsilon_0(\varepsilon_r - 1)}{\alpha_0}$$





$$\langle U^2 \rangle = 4kTR\Delta\nu$$

The present definition of the kelvin

- From 2019 the kelvin is defined:
  “by taking the fixed numerical value of the Boltzmann constant k to be $k = 1.380649 \cdot 10^{-23}$ when expressed in the units JK^{-1}”

- The kelvin is chosen in such a way that makes the Boltzmann constant exactly equal to $1.380649 \cdot 10^{-23}$ JK^{-1}

- Abstract definition

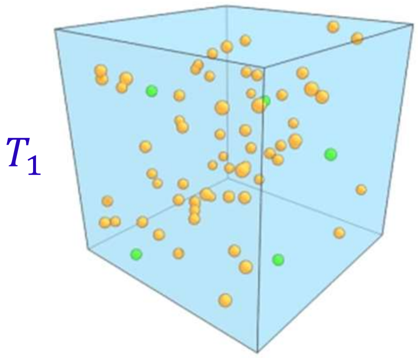
- Related to a fundamental constant of nature (the Boltzmann constant)

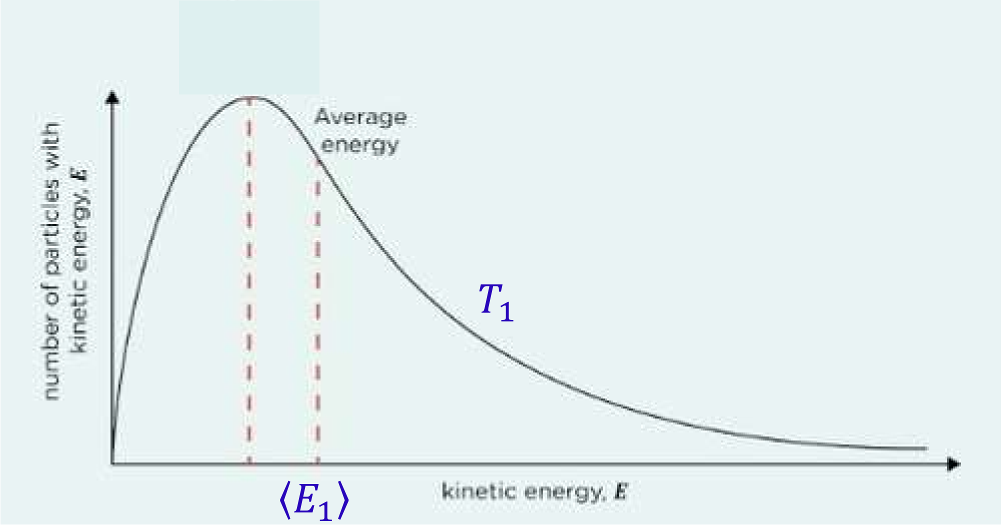
- Advantage: disconnected from material artifacts, space- and time-invariant

- Disadvantage: difficult to grasp

Understanding the present definition of the kelvin

- Consider an ideal (monoatomic) gas at equilibrium at temperature T_1:
  - The PDF of the kinetic energy of its molecules is the Maxwell-Boltzmann PDF for T_1
  - $\langle E_1 \rangle$ is the average kinetic energy for the molecules of the gas at T_1

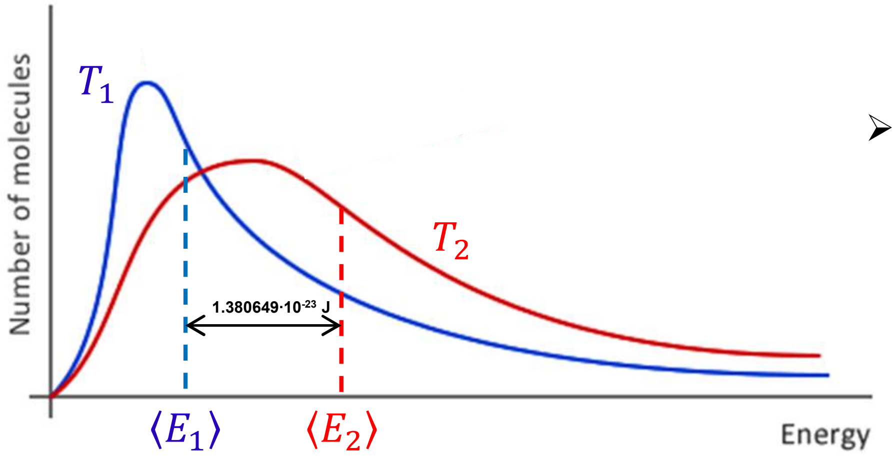




Understanding the present definition of the kelvin

- Now consider the distribution of the energies when the gas is at another (higher) temperature T_2:
  - $\langle E_1 \rangle$ is the mean kinetic energy for the molecules of the gas at T_1
  - $\langle E_2 \rangle$ is the mean kinetic energy for the molecules of the gas at T_2

- **When the difference $\langle E_2 \rangle - \langle E_1 \rangle$ is exactly 1.380649·10^{-23} J, then $T_2 - T_1 = 1\ K$**



- The kelvin is: the change of thermodynamic temperature that results in a change of mean thermal energy of 1.380649·10^{-23} J for the molecules of the system

The Consultative Committee for Thermometry (CCT)

➢ One of the 10 CCs of the CIPM

- Established in 1937
- 25 members and 3 official observers
- 9 WGs + 8 TGs
- Meets every 2 to 3 years
- Last meeting held in May 2024
- President: Dr. Dolores del Campo Maldonado, CEM, Spain

CCT

Terms of reference of the CCT

- Specific objectives of the CCT (besides those in common with the other CCs):
  - “*To ensure that the SI unit of* ***temperature and derived quantities*** *are realized and disseminated worldwide in a uniform and appropriate manner. Derived quantities include:* ***humidity and moisture, thermophysical quantities and thermal energy (heat)****.*
  - *To provide recommendations to the CIPM for the realization and dissemination of the kelvin and derived quantities.*
  - *To support the NMIs provision of traceability to thermal metrology quantities, such as through provision guidance documents and training materials*
  - *To encourage NMIs to address emerging thermal metrology needs*
  - *To provide definitive guidance on thermal metrology to users.*”

The Working Groups (WGs) of the CCT

- 8 different WGs, covering the different fields and aspects of its responsibility:
  - **WG-SP:** Strategic Planning
  - **WG-CTh:** Contact Thermometry
  - **WG-NCTh:** Non-Contact Thermometry
  - **WG-Hu:** Humidity
  - **WG-KC:** Key Comparisons
  - **WG-CMC:** Calibration and Measurement Capabilities
  - **WG-Env:** Environment
  - **WG-DIG:** Digitalization
  - **WG-ThQ:** Thermophysical Quantities

The Taskg Groups (TGs) of the CCT

- 8 different TGs (WGs act on a long-term basis, while a TG carries out a limited-time restricted mission):
  - **TG-CTh-ET:** Emerging technologies
  - **TG-Env-AirT:** Air temperature
  - **TG-NCTh-BTM:** Body temperature measurements
  - **TG-CTh-CalMed:** Guide on calibration media
  - **TG-CTh-IPRT:** Guide on industrial platinum resistance thermometry
  - **TG-NCTh-IRadT:** Guide on industrial radiation thermometry
  - **TG-CTh-TC2:** Guide on thermocouples, part 2
  - **TG-FTT:** Future Temperature Traceability

CCT-WG-KC

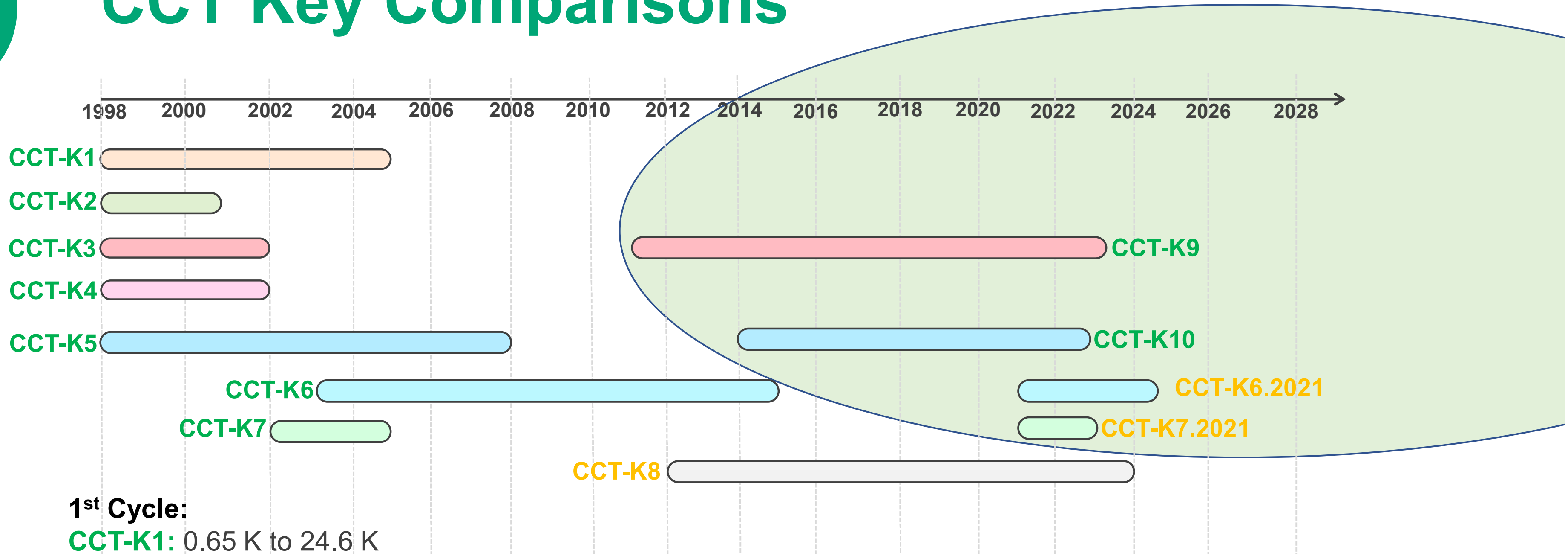
- The comparison process is defined by:
  - The CIPM-MRA-G-11 document *Measurement comparisons in the CIPM MRA: Guidelines for organizing, participating and reporting (2021)* (https://www.bipm.org/en/cipm-mra/cipm-mra-documents)
  - CCT-specific rules

- CCT-specific rules:
  - CIPM and RMO KCs:
    - Technical Protocols and Final Reports must be formally approved by the WG-KC
  - RMO SCs:
    - Can be agreed, conducted and evaluated within the respective RMO
    - On request, the WG-KC reviews both Technical Protocol and Final Report

CCT-WG-KC check-lists for comparison pilots

- To help pilots prepare Technical Protocols and Final Reports, the WG-KC developed check-lists to be used when preparing comparison protocols and reports.
- These check-lists can help improving the quality of protocols and reports, particularly in the case of unexperienced pilots
- These check-lists could be useful also for the other CCs
- See: **d1352c60-eea8-99cb-b281-4c295617e773 (bipm.org)**

CCT Key Comparisons



1st Cycle:

CCT-K1: 0.65 K to 24.6 K
CCT-K2: 13.8 to 273.16 K
CCT-K3: -189.3442 °C to 660.323 °C
CCT-K4: 660.323 °C and 961.78 °C
CCT-K5: 961°C to 1700 °C
CCT-K6: -50°C to 20 °C (frost/dew point)
CCT-K7: 273.16 K
CCT-K8: 30°C to 90 °C (dewpoint)

2nd Cycle:

CCT-K9: 2nd cycle of CCT-K3
CCT-K10: 2nd cycle of CCT-K5 (up to 3000 °C)
CCT-K7.2021: 2nd cycle of CCT-K7
CCT-K6.2021: 2nd cycle of CCT-K6

CMC Review Protocols: general principles

- Practical, pragmatic technical guidelines designed to let the CMC review process proceed according to:
  - A set of objective numerical criteria
  - Specified technical evidence
- Scientifically based:
  - Judge CMC on its technical merit
  - Remove political discussions
  - Reduce the possibility of disagreement
- Uniformly applied across all RMOs
- Publicly available in the BIPM website: https://www.bipm.org/en/committees/cc/cct/publications

List of CMC Review Protocols

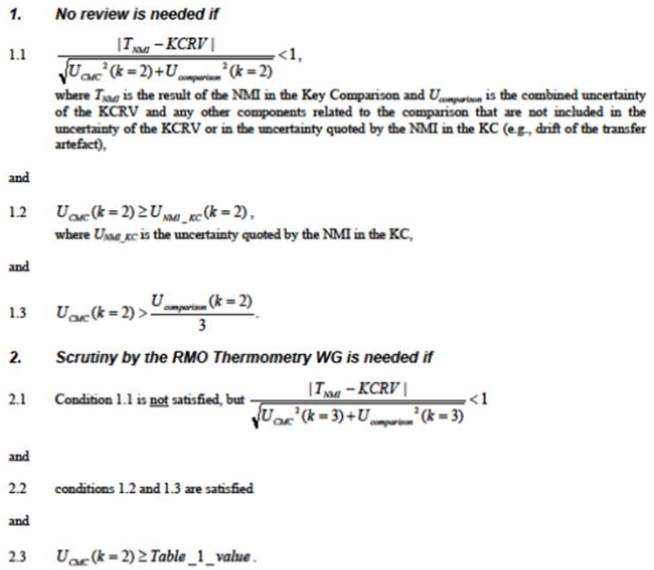
1. Calibration of fixed point cells (excluding the TPW) and calibration of SPRTs at fixed points
2. TPW
3. Calibration of high temperature fixed points
4. ITS-90 SPRT Subrange
5. Calibration of industrial thermometers
6. Radiation thermometry

7. Humidity (dew-point temperature)
8. Relative humidity
9. Humidity generators

10. Thermal diffusivity
11. IR spectral emissivity

CMC Review Protocols: key elements

- Agreed **cutoff criteria** based on literature uncertainty values
- Agreed **list of specific evidence items** required for CMC acceptance
- **Mathematical algorithms** involving KC data and claimed CMC uncertainty to review a CMC (for example, involving U_{CMC}, $U_{\mathrm{NMI\ KC}}$, $T_{\mathrm{NMI}} - KCRV$, …)
- Satisfactory participation in pertinent KC/SC
- Level of scrutiny increases as uncertainty value decreases



1. *No review is needed if*

1.1 $$\frac{|T_{NMI} - KCRV|}{\sqrt{U_{CMC}^{2}(k=2) + U_{comparison}^{2}(k=2)}} < 1,$$

where T_{NMI} is the result of the NMI in the Key Comparison and $U_{comparison}$ is the combined uncertainty of the KCRV and any other components related to the comparison that are not included in the uncertainty of the KCRV or in the uncertainty quoted by the NMI in the KC (e.g., drift of the transfer artefact),

and

1.2 $U_{CMC}(k=2) \geq U_{NMI\_KC}(k=2)$,

where U_{NMI_KC} is the uncertainty quoted by the NMI in the KC,

and

1.3 $U_{CMC}(k=2) > \frac{U_{comparison}(k=2)}{3}$.

2. *Scrutiny by the RMO Thermometry WG is needed if*

2.1 Condition 1.1 is <u>not</u> satisfied, but $\frac{|T_{NMI} - KCRV|}{\sqrt{U_{CMC}^{2}(k=3) + U_{comparison}^{2}(k=3)}} < 1$

and

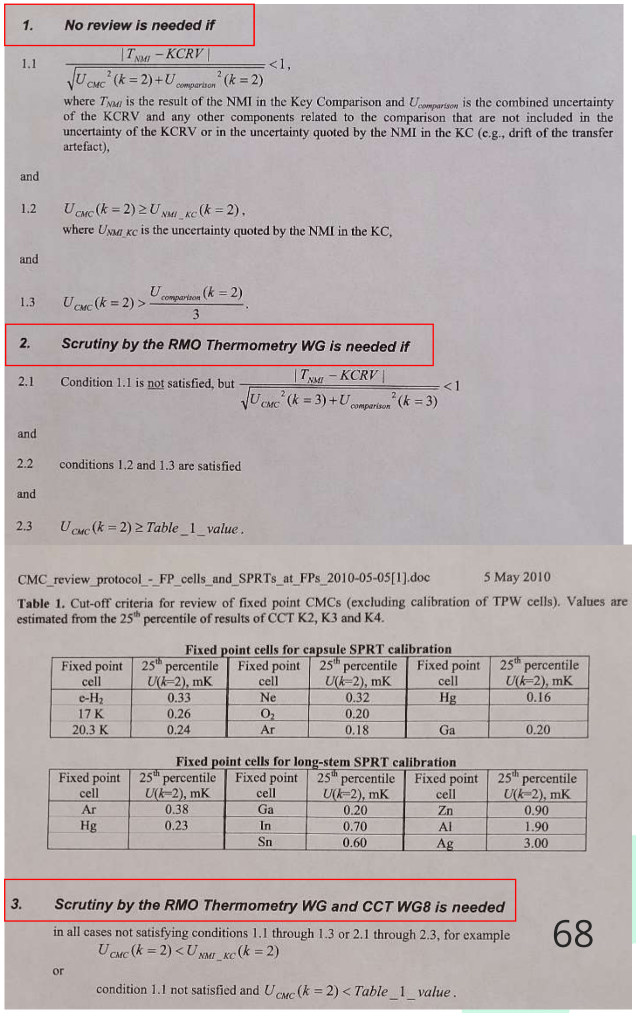
2.2 conditions 1.2 and 1.3 are satisfied

and

2.3 $U_{CMC}(k=2) \geq Table\_1\_value$.

CMC Review Protocols: three-tier review screening

- For most review protocols, a three tier review screening process identifies the level of review required for the CMC acceptance:
  - Tier 1: No RMO-level detailed review required
  - Tier 2: RMO-level detailed review required
  - Tier 3: CCT WG-CMC-level detailed review required



1. No review is needed if

1.1 $$\frac{|T_{NMI} - KCRV|}{\sqrt{U_{CMC}{}^2(k=2) + U_{comparison}{}^2(k=2)}} < 1,$$

where T_{NMI} is the result of the NMI in the Key Comparison and $U_{comparison}$ is the combined uncertainty of the KCRV and any other components related to the comparison that are not included in the uncertainty of the KCRV or in the uncertainty quoted by the NMI in the KC (e.g., drift of the transfer artefact),

and

1.2 $U_{CMC}(k=2) \geq U_{NMI\_KC}(k=2)$,

where U_{NMI_KC} is the uncertainty quoted by the NMI in the KC,

and

1.3 $$U_{CMC}(k=2) > \frac{U_{comparison}(k=2)}{3}.$$

2. Scrutiny by the RMO Thermometry WG is needed if

2.1 Condition 1.1 is not satisfied, but $\frac{|T_{NMI} - KCRV|}{\sqrt{U_{CMC}{}^2(k=3) + U_{comparison}{}^2(k=3)}} < 1$

and

2.2 conditions 1.2 and 1.3 are satisfied

and

2.3 $U_{CMC}(k=2) \geq Table\_1\_value$.

CMC_review_protocol_-_FP_cells_and_SPRTs_at_FPs_2010-05-05[1].doc 5 May 2010

Table 1. Cut-off criteria for review of fixed point CMCs (excluding calibration of TPW cells). Values are estimated from the 25th percentile of results of CCT K2, K3 and K4.

Fixed point cells for capsule SPRT calibration

Fixed point cell	25th percentile $U(k=2)$, mK	Fixed point cell	25th percentile $U(k=2)$, mK	Fixed point cell	25th percentile $U(k=2)$, mK
e-H_2	0.33	Ne	0.32	Hg	0.16
17 K	0.26	O_2	0.20		
20.3 K	0.24	Ar	0.18	Ga	0.20

Fixed point cells for long-stem SPRT calibration

Fixed point cell	25th percentile $U(k=2)$, mK	Fixed point cell	25th percentile $U(k=2)$, mK	Fixed point cell	25th percentile $U(k=2)$, mK
Ar	0.38	Ga	0.20	Zn	0.90
Hg	0.23	In	0.70	Al	1.90
		Sn	0.60	Ag	3.00

3. Scrutiny by the RMO Thermometry WG and CCT WG8 is needed

in all cases not satisfying conditions 1.1 through 1.3 or 2.1 through 2.3, for example

$U_{CMC}(k=2) < U_{NMI\_KC}(k=2)$

or

condition 1.1 not satisfied and $U_{CMC}(k=2) < Table\_1\_value$.

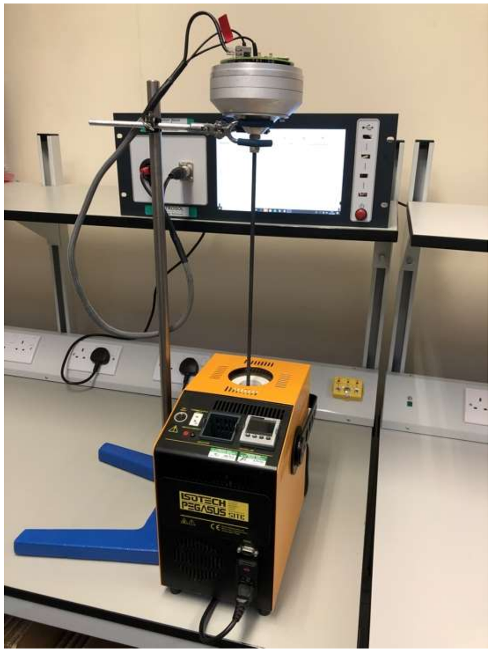
Traceability and dissemination

- Two ways of measuring temperature:
  1. Thermodynamic temperature ***T*** via primary thermometry methods
  2. Use a thermometer calibrated, either directly or through a chain of calibration, to the ITS-90: $\boldsymbol{T_{90}}$

- Until recently, for all practical purposes, the ITS-90 temperature T_{90} has been used

- Things are changing:
  - Advancement of primary thermometry techniques
  - Use **practical primary thermometers** to directly access and disseminate T

- MePK-2019: "*In the future, as the primary methods evolve and are expected to achieve lower uncertainties,* ***primary thermometers will become more widely used and gradually replace the ITS-90*** *and the PLTS-2000 as the basis of temperature measurement*"



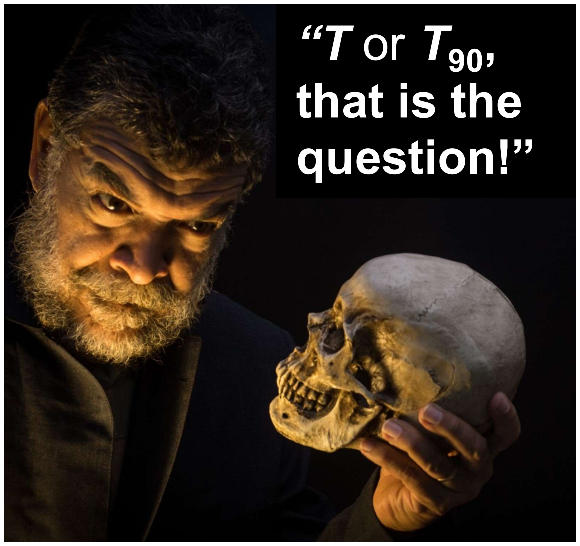
Mixed Dissemination Environment (MDE)

P.M.C. Rourke, Future of the International Temperature Scale in a Mixed Dissemination Environment, *ITS10* (2024)

- We are living a transition:
  1. From present universal T_{90} dissemination
  2. To future universal T dissemination

- The transition could be not as smooth as we wish for, because different NMIs will develop primary thermometry capabilities at different times and in different ranges:
  - Some users will get T_{90}-calibrated thermometers
  - Other users will get T-calibrated thermometers

- Confusion among the user community:
  - T and T_{90} are not equivalent
  - In the core LSPRT range, the difference between T and T_{90} is more than 10 times bigger than ITS-90 calibration uncertainty $u(T_{90})$



Future traceability and dissemination

- Has been discussed in a recent CCT Workshop in Paris this past May

- Will be further discussed in a Royal Society Theo Murphy Discussion Meeting, on 24-25 February 2025, Glasgow, UK (≈ 200th anniversary year of Lord Kelvin's birth)

- To minimize the disruption, Patrick Rourke (NRC) proposed to introduce a new thermodynamically-accurate **ITS-XX:**
  - If we first replace $\boldsymbol{T_{90}}$ with $\boldsymbol{T_{XX}}$ (thermodynamically accurate), then the transition $\boldsymbol{T_{XX}} \rightarrow \boldsymbol{T}$ would be smooth

A proposal for a new ITS

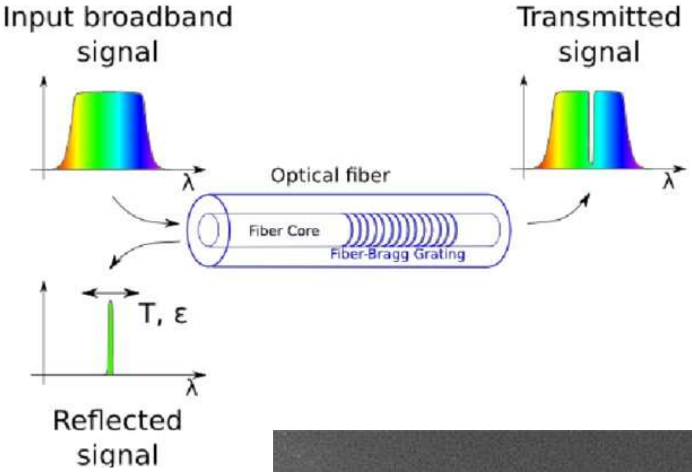
P.M.C. Rourke, Future of the International Temperature Scale in a Mixed Dissemination Environment, *ITS10* (2024)

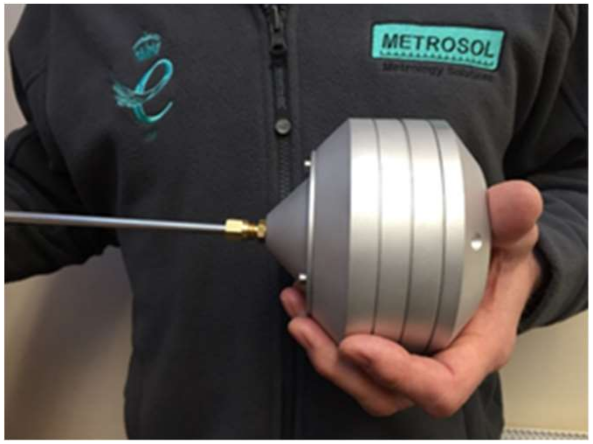
- Main features of the proposed **ITS-XX**:
  - Keep the same fixed points, interpolating instruments and interpolation functions as the ITS-90
  - Change the SPRT reference function numerical coefficients and values at the fixed points
  - Introduce Xe, CO_2 and SF_6 triple points as acceptable alternatives to the Hg point. The Hg point would stay in the scale for those labs that still want to use it.
- It would transform the ITS-90 into a thermodynamically-accurate scale
- It could be easily implemented, using existing equipment, by updating tables of reference function coefficients and fixed point values in the software codes.

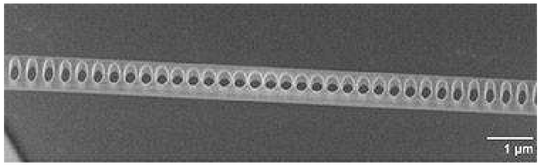
Requirements for a new scale

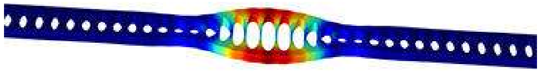
- CCT Meeting 2024 acknowledged this possibility and requested to determine **the requirements for a possible new scale:**
    - New thermodynamic temperature data above 400 K (we need to know T - T_{90} with a better uncertainty)
    - A viable substitution of the Hg TP (further R&D on Xe, CO_2 and SF_6 TPs and LSPRT-compatible Xe-TP system)
    - Merge PLTS-2000 into ITS-XX (solve PLTS-2000 inconsistency in ^{3}He melting pressure equation)
    - Solve HTSPRT problems (retain HTSPRTs or use Au-Pt thermocouples instead?)

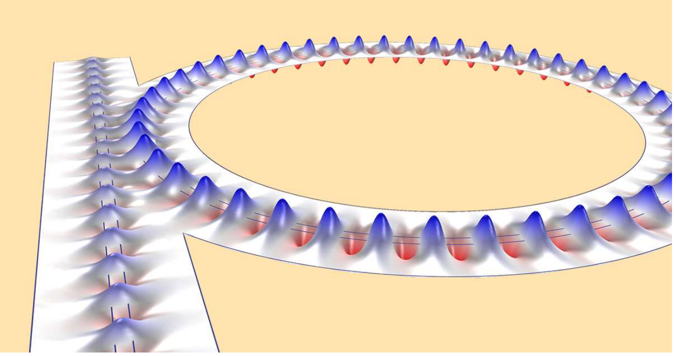
Emerging technologies in thermometry



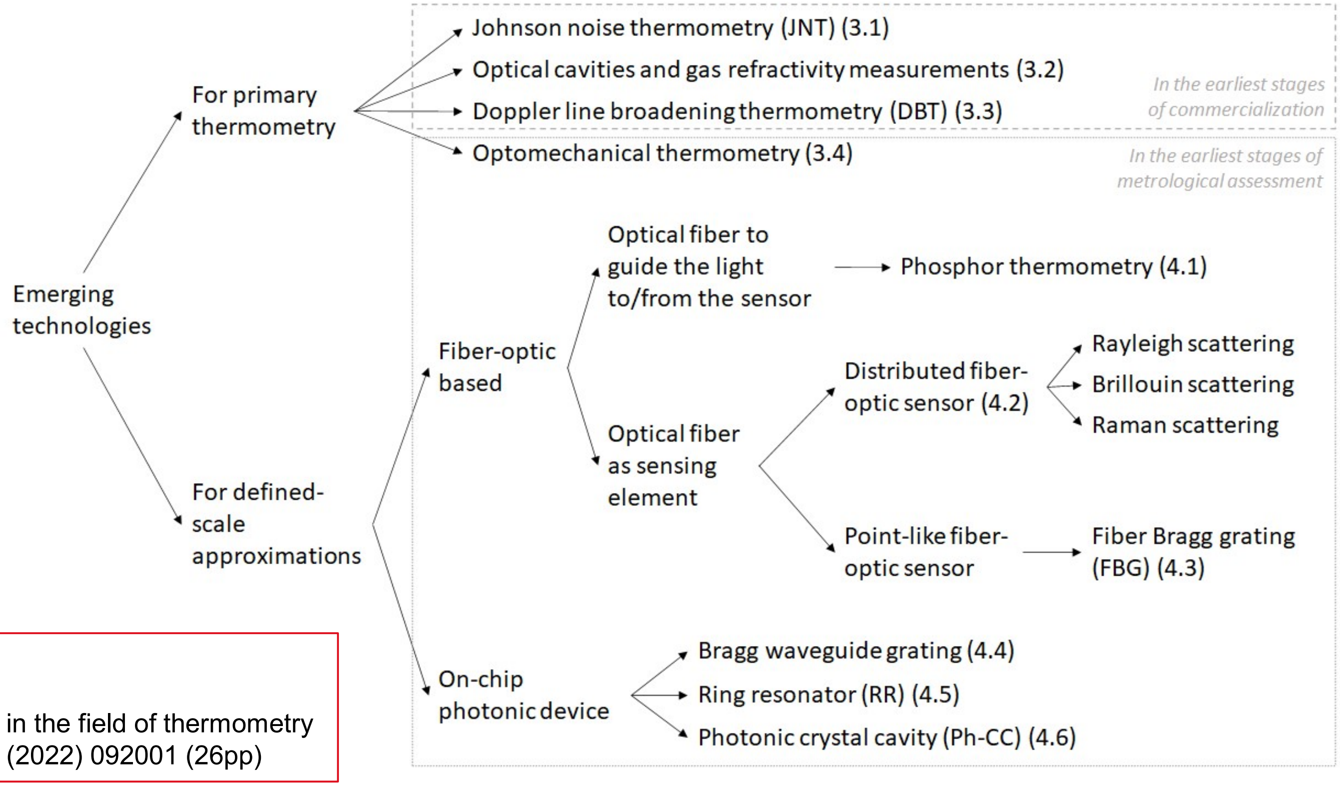








Emerging technologies in thermometry



Emerging technologies

For primary thermometry

Johnson noise thermometry (JNT) (3.1)

Optical cavities and gas refractivity measurements (3.2)

Doppler line broadening thermometry (DBT) (3.3)

In the earliest stages of commercialization

Optomechanical thermometry (3.4)

In the earliest stages of metrological assessment

For defined-scale approximations

Fiber-optic based

Optical fiber to guide the light to/from the sensor

Phosphor thermometry (4.1)

Optical fiber as sensing element

Distributed fiber-optic sensor (4.2)

Rayleigh scattering

Brillouin scattering

Raman scattering

Point-like fiber-optic sensor

Fiber Bragg grating (FBG) (4.3)

On-chip photonic device

Bragg waveguide grating (4.4)

Ring resonator (RR) (4.5)

Photonic crystal cavity (Ph-CC) (4.6)

Review Article:
S. Dedyulin et al.
Emerging technologies in the field of thermometry
Meas. Sci. Technol. **33** (2022) 092001 (26pp)

Emerging technologies in thermometry

Technology	Principle	Proposed Temperature range	Best reported uncertainty
Johnson noise thermometry (JNT)	Electronic noise caused by the random thermal motion of the charge carriers within an electrical conductor.	50 nK – 2500 K	2.7 ppm @ 273 K
Optical cavities and gas refractivity	Lorentz-Lorentz equation: relationship between the refractive index, pressure, temperature and molar electric and magnetic polarizability in a gas.	100 K – 400 K	12 ppm @ 293 K
Doppler-line broadening thermometry (DBT)	In a gas at thermodynamic equilibrium, the distribution of velocities of its molecules causes a broadening of its spectral lines (due to the Doppler effect). The width of the broadening depends on temperature.	300 K – 1000 K	71 ppm @ 296 K
Optomechanical thermometry	Optically measure Brownian motion of nanomechanical resonator. Measure quantum backaction via correlations between optical force and induced motion.	0.05 K – 300 K	7.5% @ 40 K
Fiber-coupled phosphor thermometry	Photoluminescence of phosphors: the exponential decay time depends on temperature.	77 K – 2000 K	860 ppm @ 673 K
Fiber optic thermometry, based on Raman, Brillouin and Rayleigh scattering	Distributed fiber optic sensor measures changes in the backscattered light over the entire length of an optical fiber. Backscattering includes Rayleigh, Brillouin and Raman scattering.	250 K – 470 K (Rayl.) 250 K – 350 K (Brill.) 250 K – 350 K (Ram.)	n.a.
Fiber-Bragg-Grating (FBG) Thermometry	Periodic modulation of the refractive index in an optical fiber creates interference for a specific light wavelength. A temperature change affects the grating period.	80 K – 1300 K	610 ppm @ 393 K
Ring-Resonator (RR) thermometry	A closed-loop optical waveguide evanescently coupled to an adjacent optical waveguide. The resonant wavelength of waves is temperature dependent.	3 K – 1000 K	10 mK @ 353 K
Photonic-crystal-cavity (PhCC) thermometry	Wavelength-scale Fabry-Perot cavity sensitive to temperature-induced changes in effective length.	3 K – 1000 K	510 ppm @ 343 K

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SIM METROLOGY SCHOOL

Thanks!

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