NPL National Physical Laboratory

The emergence of temperature scales: From pre-1600s to ITS-90

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“100”-year anniversary celebration of international temperature scales, CCT: 21 May 2026

Introduction

- Emergence of reliable thermometry
  1. Thermoscope to thermometer
  2. “Practical” temperature scales
- The “light dawns”
  1. Physical understanding of temperature, classical thermodynamics
  2. Primary thermometry
  3. Emergence of defined temperature scales
- International Temperature Scales
  1. Precursor: Normal hydrogen scale (1887)
  2. Leading to the defined scales ITS-27…. to…. ITS-90
- Summary

Emergence of thermometry:

1. Thermoscope to thermometer
2. “Practical” temperature scales

Emergence of thermometry:

1. Thermoscope to thermometer

A trip to Florence….

- When in Florence where do you visit?

Uffizi Art Gallery

Santa Maria del Fiore

Ponte Vecchio

A trip to Florence….

- When in Florence where do you visit?

Uffiz

BUT .. All *serious* thermometrists skip these places and make a beeline for:

The Museo Galileo, Istituto e Museo di Storia della Scienza

Why?

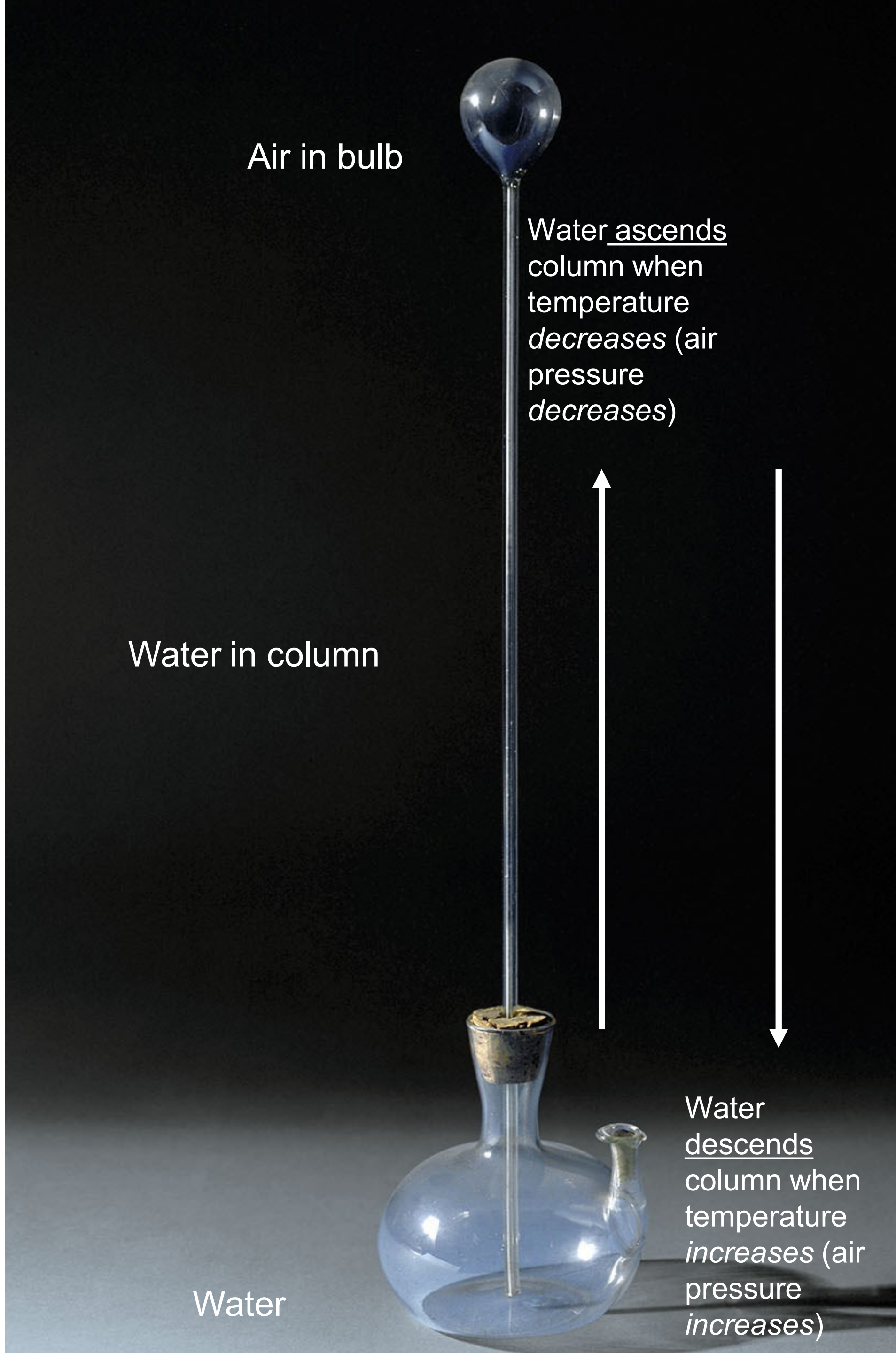
Ponte Vecchio

A trip to Florence….

- One of best collections of historic thermometers in the world
- **Who could possibly miss that!!**

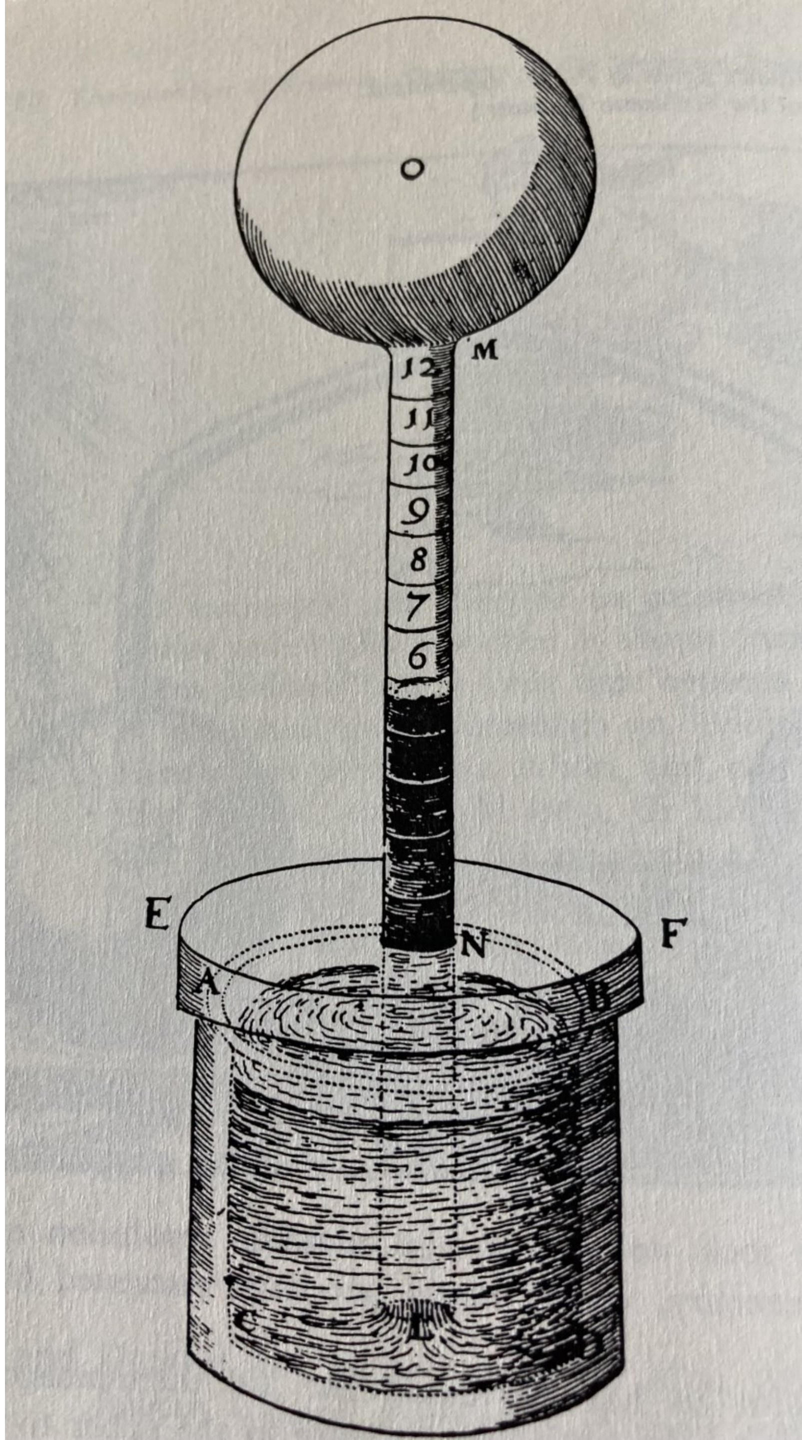

Beginnings - the thermoscope

- Principle of thermoscope known in antiquity (Philo of Byzantium & Hero of Alexandria)
- Probably (re)invented/demonstrated by Galileo (and others) during his stay in Padua (from1592)



Thermoscope to Thermometer

- By adding a “scale” the thermoscope is turned into a thermometer (Galileo did this but certainly others did it as well for e.g. Santorio Sanctorius and Robert Fludd by early 1600s)



Thermoscope to Thermometer

- Santorio thermoscope "scale" – two reference points:
- "..apply snow to the sphere of the glass instrument so that the water may ascend to its upper limit. Then with the flame of a candle we can make the water descend as far as it will go"

[Commentary on Galen's art of medicine ed II1630]

- Thermometers based on thermoscopes had a serious flaw – sensitive to changes in air pressure
- Thermometers based on water as the thermometric liquid have a serious flaw – density of water is a strong function of temperature (doesn't expand linearly with temperature e.g. max density at 4 ^{0}C and of course freezes at 0 ^{0}C)

First modern-style liquid in glass thermometer

- In 1654 Ferdinando II de'Medici, Grand Duke of Tuscany made sealed tubes part filled with alcohol – independent of air pressure – first modern thermometers (known colloquially as the "Florentine spirit-in-glass thermometer")

Florentine thermometers

- Very elaborate devices began to be made – e.g. 420 enamel scale markers indicating one of the scales of the Accademia del Cimento (founded Florence 1657)
- Scale was arbitrary for e.g. calibrated at the two fixed points of *snow* and of the "hottest day in Florence"
- … many empirical "practical" temperature scales emerging around that time

Photo: acknowledgement Museo Galileo, Firenze

Emergence of thermometry:

2. “Practical” temperature scales

Many “practical” temperature scales

- In the 17-18th Century thermometers were usually liquid-in-glass, mainly alcohol, but as the century progressed mercury was increasingly used
- There *were* many “practical” temperature scales in use
- Chang: “by the late 17th century thermometers were very fashionable but still notoriously unstandardised” – ie **there were no formally agreed fixed points with no formally agreed temperatures** [Chang: Inventing Temperature OUP]

Royal Society Thermometer with “inverted” scale

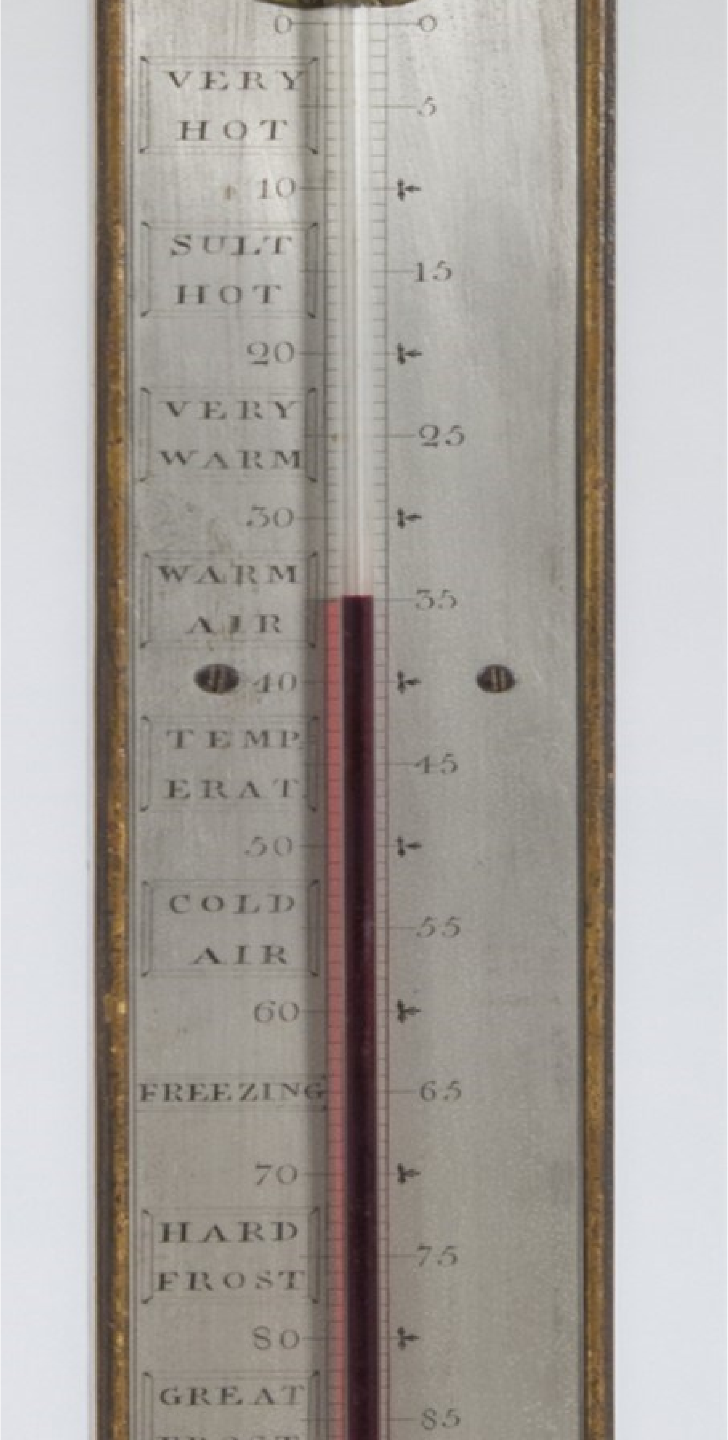
“Royal Society Scale” ~1720’s

0° greatest heat

65° freezing point (of water)

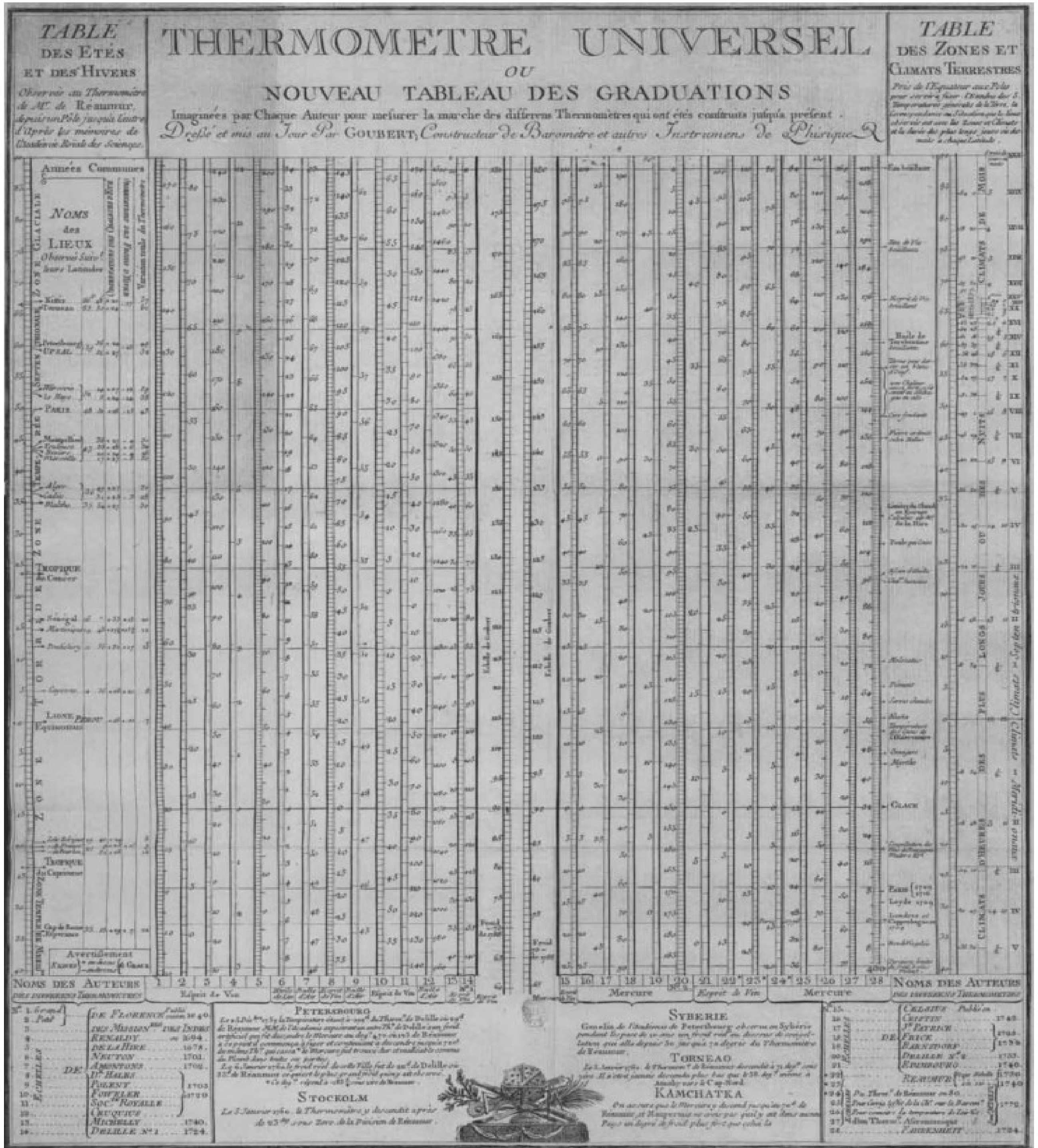
[possibly inverted to *mimic* the action of the thermoscope]

Courtesy of: Museum of the History of Science, University of Oxford



Thermometer with 18 scales, 1754, University Museum, Utrecht, the Netherlands

Conversion table of practical scales with 28 different scales (ca 1789)



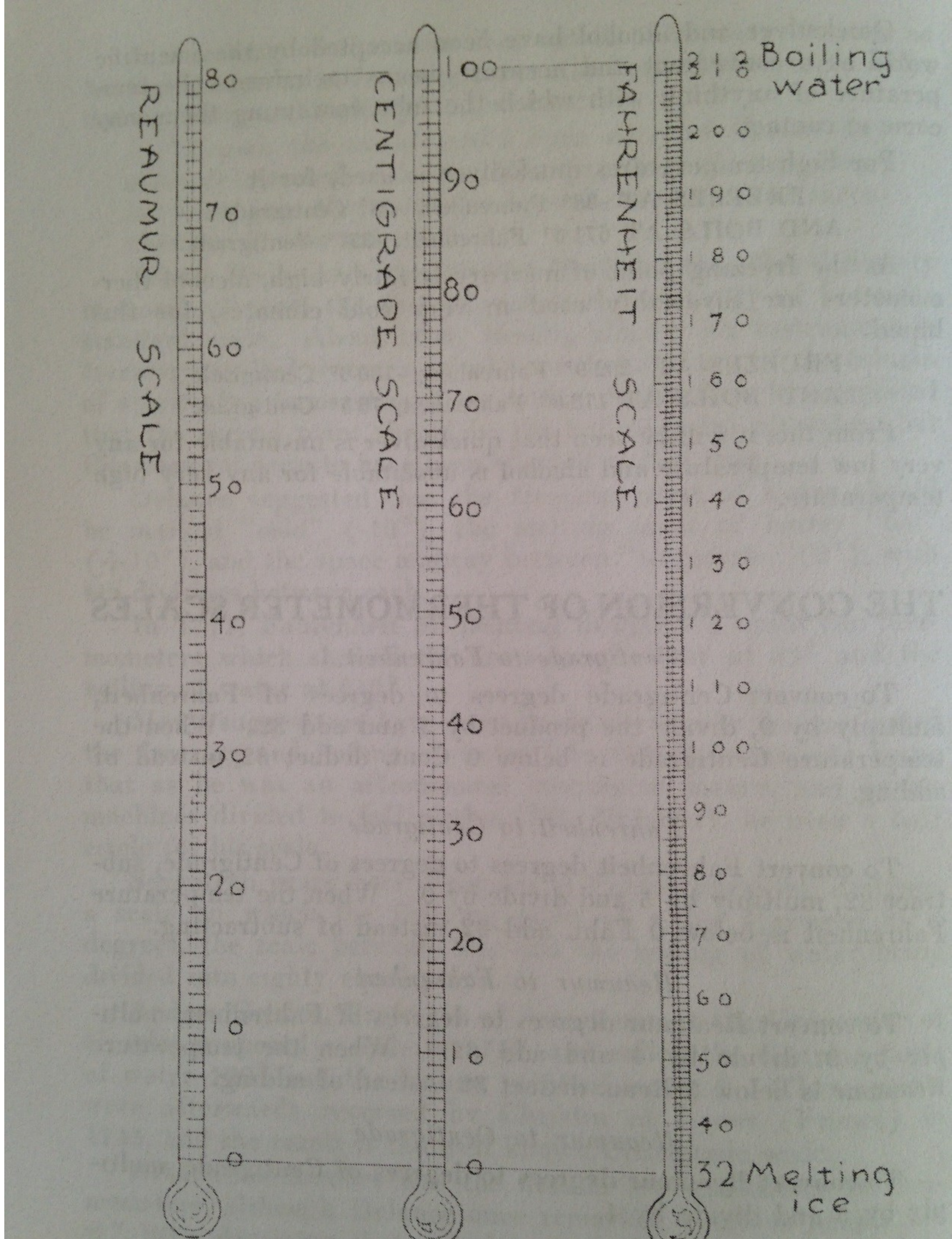
Bibliothèque nationale de France, Paris

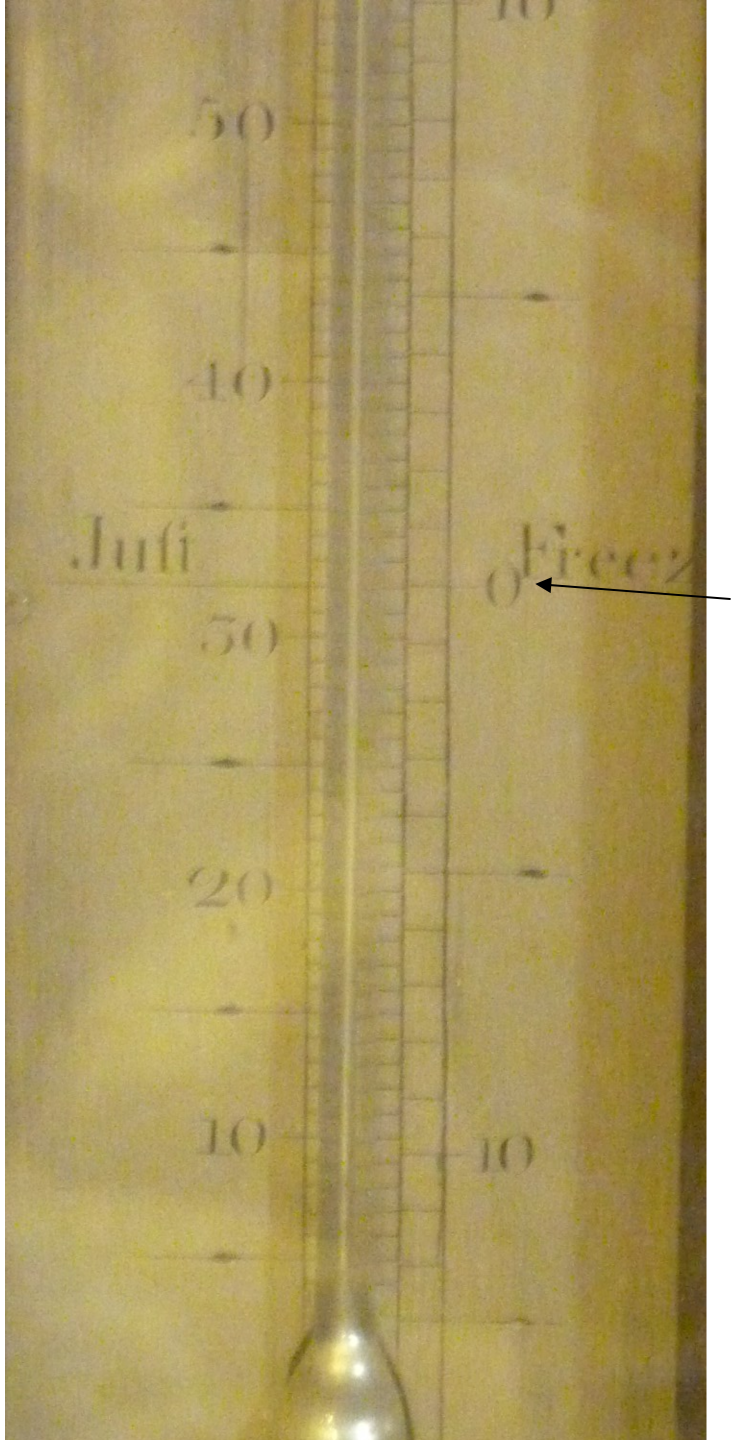
The many "practical" temperature scales

- These temperature scales were *arbitrary*, based on "fixed" points whose temperature was *fixed* by convention
- Typical fixed points were; melting ice and the boiling point of water, human body temperature, more unusual ones e.g. freezing aniseed oil, melting butter, "the temperature of a very deep cellar under the Paris Observatory" " (Mariotte – French Academy of Sciences)
- But by the beginning of 19th Century there were 3 main temperature scales in use – all having their origins in the first half of the 18th Century

Three main scales in use at beginning of 19th Century

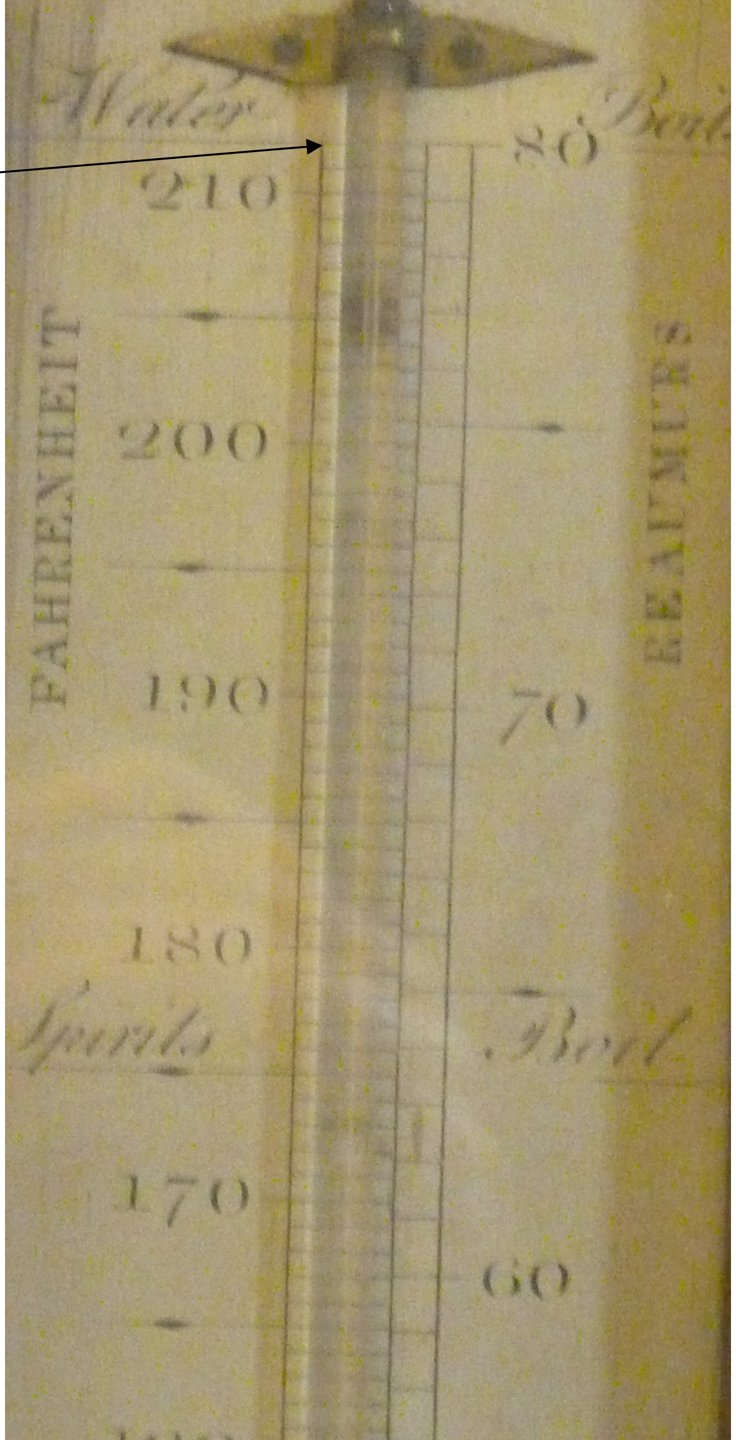
Fahrenheit / ºF (in 1724)
Réaumur / ºRé (in 1731)
Centigrade / ºC (in 1741, initially inverted type scale)





Boiling point on Fahrenheit and Réaumur scale

Freezing point on Fahrenheit and Réaumur scale



Practical scales – towards a physical understanding of temperature

- As 18th Century progressed thermometer manufacturing improved (became more standardised) and thermometers *were* increasingly reproducible BUT *the temperature values still had no physical significance*
- In the 19th Century – that was set to change…

The “light dawns”

1. Physical understanding of temperature
2. Primary thermometry
3. Emergence of defined temperature scales

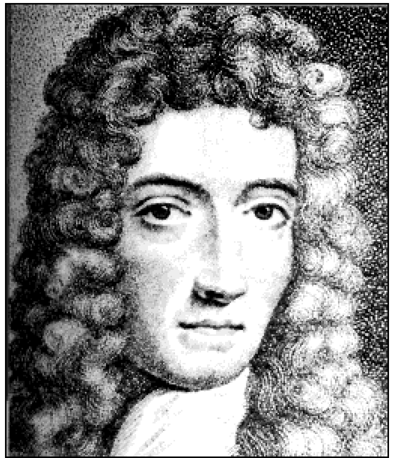
The “light dawns”

1. Physical understanding of temperature – classical thermodynamics

The emergence of a physical understanding of temperature

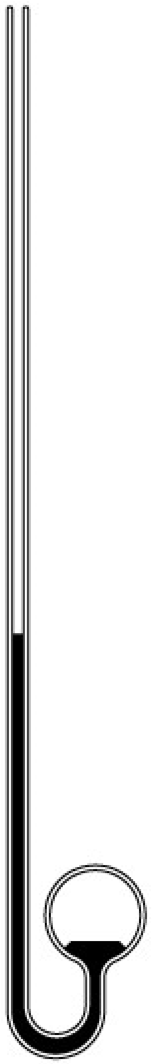
- Basic "*Primary*" "thermometers" were already known (e.g. <u>air</u> thermometers of Amontons and Boyle)
- Important physical principles had been discovered – e.g. Boyle's law: Pressure x Volume = Constant

(at constant "temperature")



Robert Boyle 1627-1691

Amontons quantitative air thermometer (~1690s) – later sealed (~1708) at the open end (and filled like a siphon to eliminate air in the column)



The emergence of a physical understanding of temperature

- French Natural Philosophers such as Amontons [1663-1705], Carnot and Regnault
- Experimental findings of James Joule
- Was there something fundamental underlying the diversity of "practical" temperature scales?
- William Thomson (later Lord Kelvin) "Stood on the shoulders of these giants" and slowly but surely "saw further"

The emergence of a physical understanding of temperature Carnot

- In 1824 French engineer Sadi Carnot published short treatise Réflextons sur la puissance motrice du feu: (Reflections on the motive power of fire)
- First description of maximum possible efficiency of heat engines
- Thomson, on reading it in 1848, called it "*an epoch-making gift to science*"

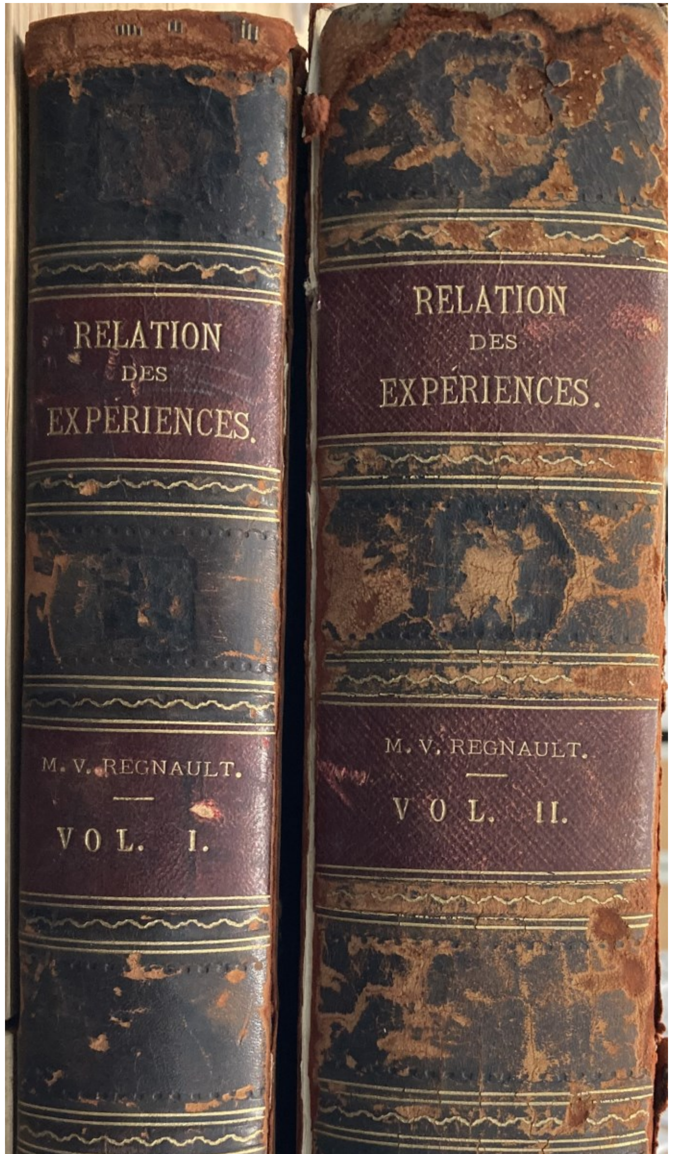
Sadi Carnot [1796-1832]

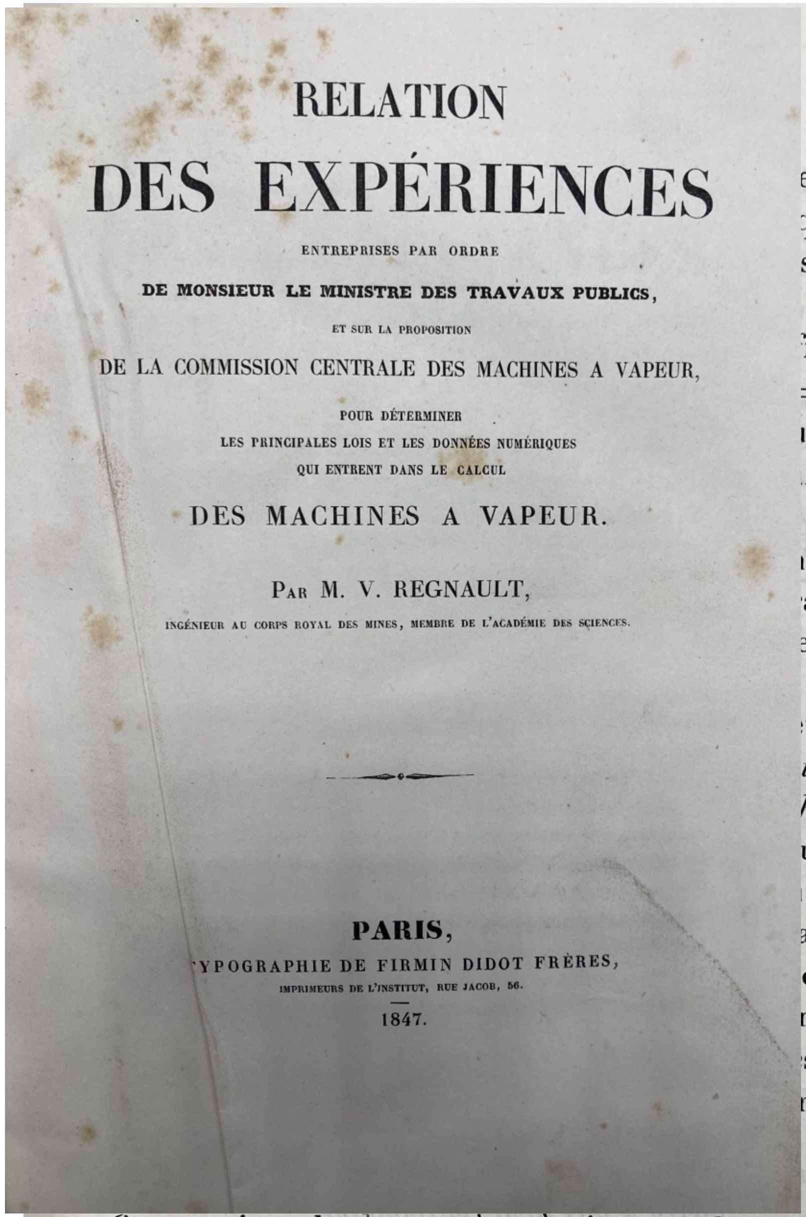
The emergence of a physical understanding of temperature - Regnault

- Formidable French experimentalist Regnault published in 1847 on “comparability of gas thermometers”
- Provided the experimental platform for classical thermodynamics
- Thomson .. acknowledging his debt to Regnault said he learned from him “*a love of precision in all things, and the highest virtue of an experimenter - patience*”

Henri Regnault1810-1878

Regnault's – constant volume gas thermometry





RELATION

DES EXPÉRIENCES

ENTREPRISES PAR ORDRE

DE MONSIEUR LE MINISTRE DES TRAVAUX PUBLICS,

ET SUR LA PROPOSITION

DE LA COMMISSION CENTRALE DES MACHINES A VAPEUR,

POUR DÉTERMINER

LES PRINCIPALES LOIS ET LES DONNÉES NUMÉRIQUES

QUI ENTRENT DANS LE CALCUL

DES MACHINES A VAPEUR.

PAR M. V. REGNAULT,

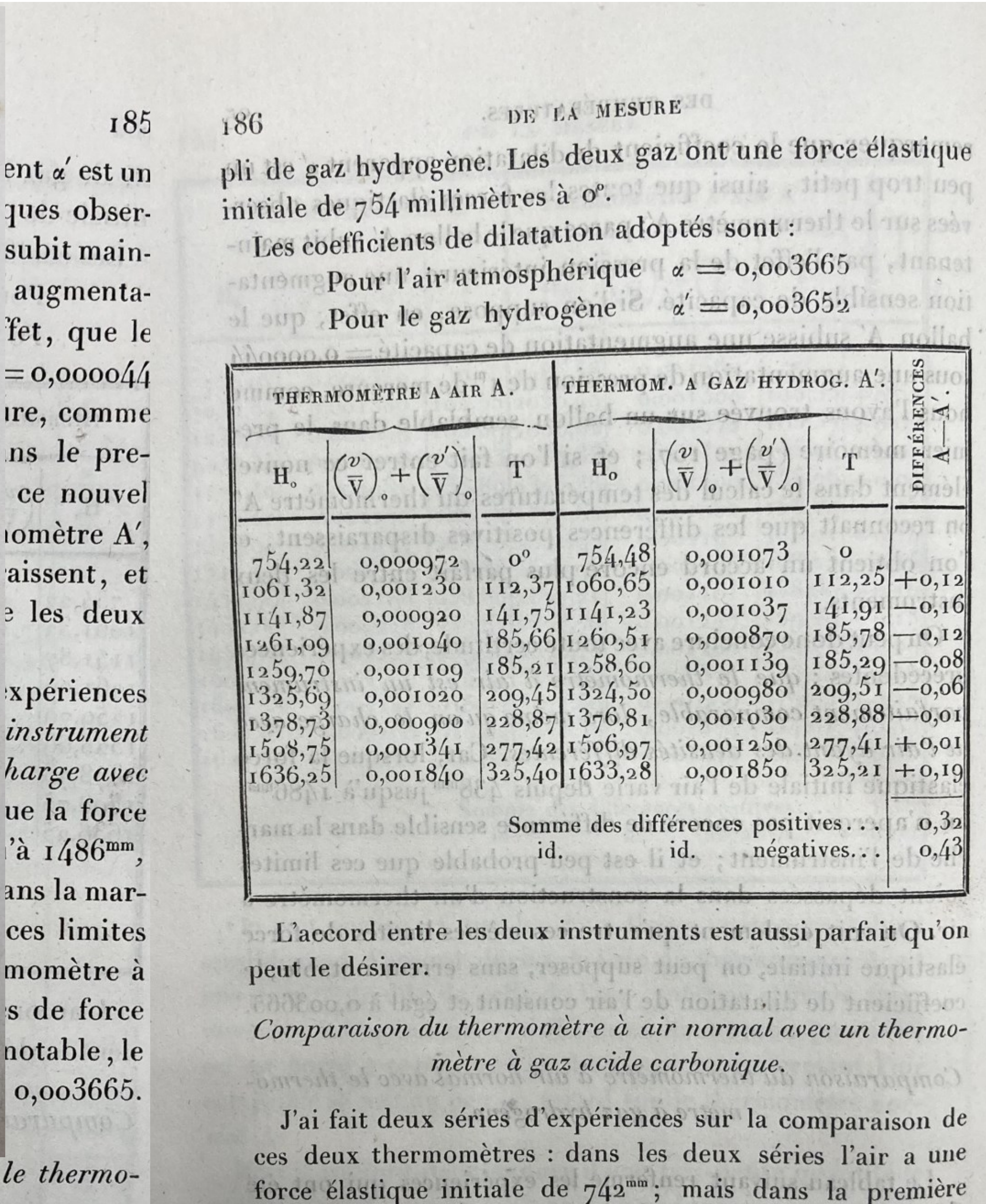
INGÉNIEUR AU CORPS ROYAL DES MINES, MEMBRE DE L'ACADÉMIE DES SCIENCES.

PARIS,

TYPOGRAPHIE DE FIRMIN DIDOT FRÈRES,

IMPRIMEURS DE L'INSTITUT, RUE JACOB, 56.

1847.



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0,003665.

Comparaison du thermomètre à air normal avec le thermo-

186 DE LA MESURE

pli de gaz hydrogène. Les deux gaz ont une force élastique initiale de 754 millimètres à 0°.

Les coefficients de dilatation adoptés sont :

Pour l'air atmosphérique $\alpha = 0,003665$

Pour le gaz hydrogène $\alpha' = 0,003652$

THERMOMÈTRE A AIR A.			THERMOM. A GAZ HYDROG. A'.			DIFFÉRENCES A—A'.
H_0	$\left(\frac{v}{V}\right)_0 + \left(\frac{v'}{V}\right)_0$	T	H_0	$\left(\frac{v}{V}\right)_0 + \left(\frac{v'}{V}\right)_0$	T	
754,22	0,000972	0°	754,48	0,001073	0	
1061,32	0,001230	112,37	1060,65	0,001010	112,25	+0,12
1141,87	0,000920	141,75	1141,23	0,001037	141,91	−0,16
1261,09	0,001040	185,66	1260,51	0,000870	185,78	−0,12
1259,70	0,001109	185,21	1258,60	0,001139	185,29	−0,08
1325,69	0,001020	209,45	1324,50	0,000980	209,51	−0,06
1378,73	0,000900	228,87	1376,81	0,001030	228,88	−0,01
1508,75	0,001341	277,42	1506,97	0,001250	277,41	+0,01
1636,25	0,001840	325,40	1633,28	0,001850	325,21	+0,19
	Somme des différences positives . . .					0,32
	id.		id.	négatives . . .		0,43

L'accord entre les deux instruments est aussi parfait qu'on peut le désirer.

Comparaison du thermomètre à air normal avec un thermomètre à gaz acide carbonique.

J'ai fait deux séries d'expériences sur la comparaison de ces deux thermomètres : dans les deux séries l'air a une force élastique initiale de 742mm ; mais dans la première

James Prescott Joule (1818-1889)
Courtesy of Royal Society

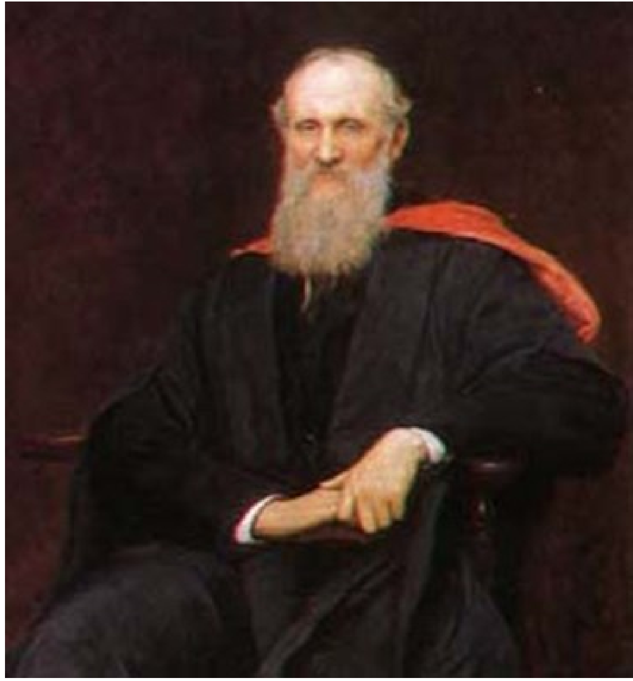
The emergence of a physical understanding of temperature– Joule

- Joule's careful experiments showed mechanical work could be converted into an *equivalent* amount of heat – through measuring temperature rises in water bath agitated by paddles moved by falling weights
- Scientific establishment initially refused to accept Joule's findings
- However collaboration between Joule and Thomson led to widespread acceptance of principle of "conservation of energy"

Cast Iron Paddle Wheel Apparatus; was given to Kelvin by Joule. It was used between 1847-1849 to obtain a determination of the Mechanical Equivalent of Heat. Courtesy Hunterian Museum - Glasgow GLAHM 113362

Joining up the dots…

- Between mid-1840s to mid-1850s Thomson drew all these ideas together and developed the first theoretical framework for absolute temperature based on a modified version of Carnot's ideal heat engine
- Key concepts were:
  - That an "absolute (**independent of substance** e.g. mercury, air etc) temperature scale existed"
  - Accepted the existence of absolute zero (following Amontons etc)
  - Accepted that heat and mechanical work were inter-convertible (conservation of energy)
- Thomson's conclusions still form the basis of modern primary gas-based thermometry today

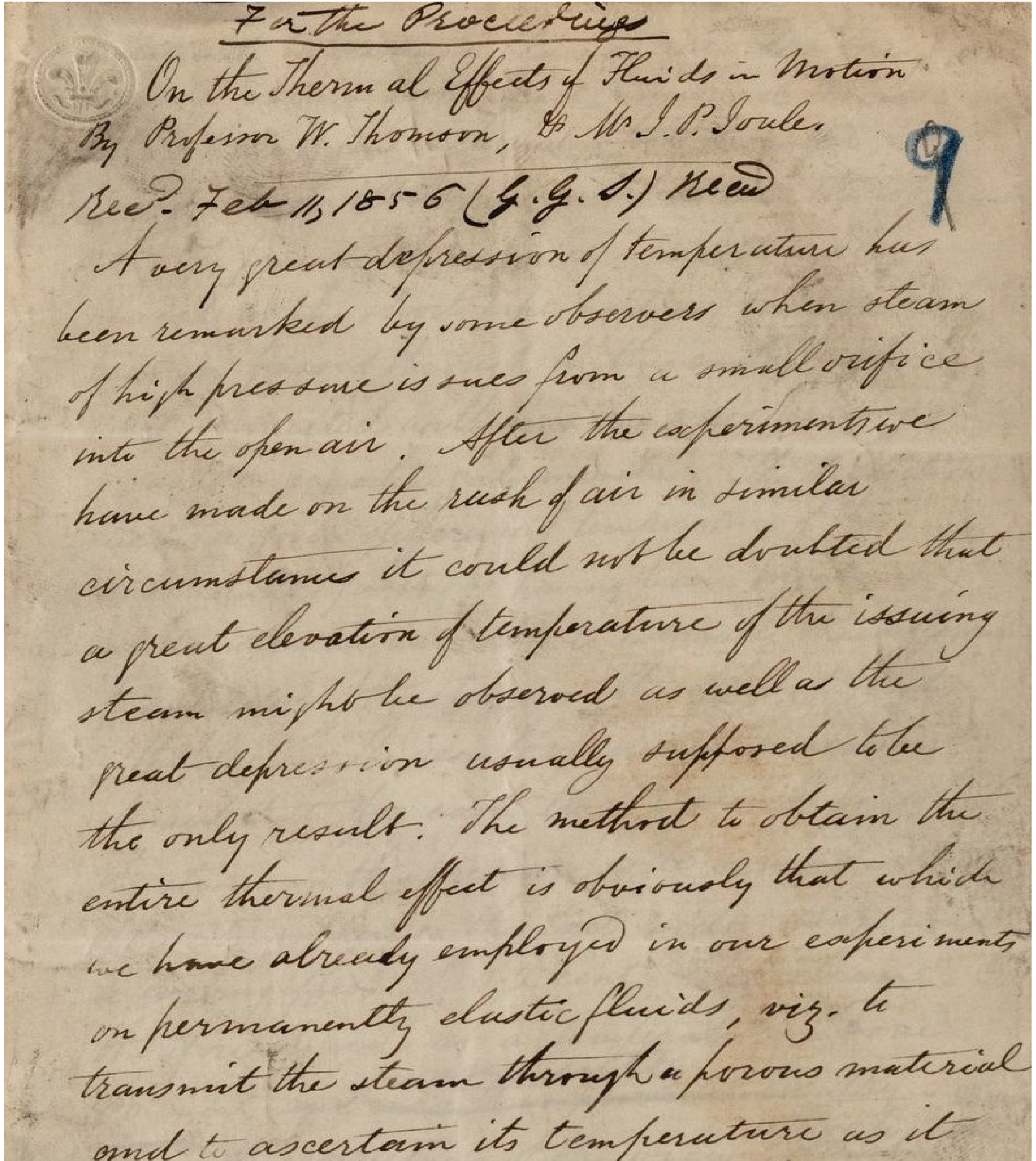


William Thomson (Lord Kelvin)
(1824 – 1907)
Courtesy Hunterian Museum - Glasgow

More details Hasok Chang "Inventing Temperature" Chapter 4

Key papers on primary thermometry – mid 1840s-1850s.

- Thomson and Joule paper (1856) “On the thermal effects of fluids in motion” reporting the idea of conservation of energy (independently discovered by Clausius and Helmholtz)


For the Proceedings
On the Thermal Effects of Fluids in Motion
By Professor W. Thomson, & Mr J. P. Joule.
Recd. Feb 11, 1856 (G. G. S.) Read
9

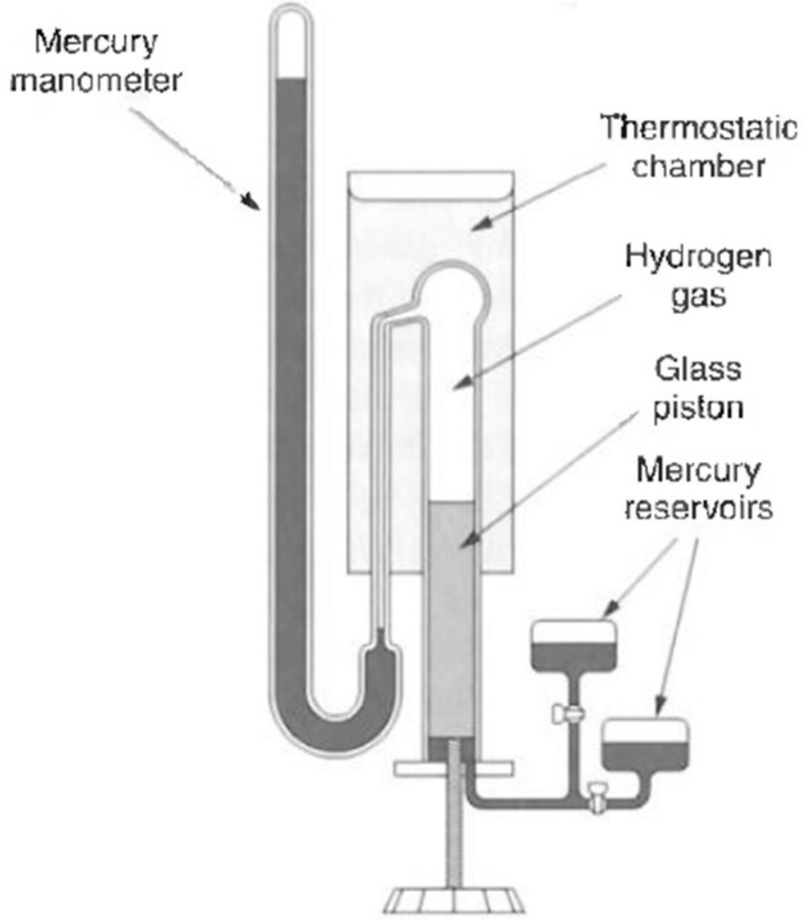
A very great depression of temperature has been remarked by some observers when steam of high pressure issues from a small orifice into the open air. After the experiments we have made on the rush of air in similar circumstances it could not be doubted that a great elevation of temperature of the issuing steam might be observed as well as the great depression usually supposed to be the only result. The method to obtain the entire thermal effect is obviously that which we have already employed in our experiments on permanently elastic fluids, viz. to transmit the steam through a porous material and to ascertain its temperature as it

The "light dawns"

2. Primary thermometry

Primary thermometry

- Primary thermometry naturally emerged from Thomson's theoretical framework
- Thermodynamic (absolute) temperatures were established using constant volume/pressure gas thermometers



A constant-pressure hydrogen-gas thermometer designed by Kelvin.

Nicolas and White Traceable Temperatures p. 13 (thanks to Howard Yoon for drawing my attention to this picture)

Primary thermometry but…

- By mid19th Century there was a growing need for *reliable physically realistic* thermometry in industry and science

- **Ideally would use (gas) thermometers that measured thermodynamic (absolute) temperature (*T*)**

- Primary thermometry was physical … but not practical…

Hugh Longbourne Callendar 1899 "It is impossible for those who have never worked with a [constant volume] gas thermometer to realise the extent of its shortcomings"

- But … practical thermometry was not physical…

- How to solve this conundrum?

The “light dawns”

3. Idea of defined temperature scales

…leading to the idea of a *defined* temperature scale

- Use *primary* thermometry to determine the *thermodynamic* temperature of a number of fixed points, [e.g.s the freezing points of water, the freezing point of tin (and other metals)]
- These known temperature fixed-points could then used to calibrate *practical* thermometers…..
- Opening the possibility of a defined scale that….

A defined scale that gives "thermodynamic" temperatures

- Was as close as practically possible to thermodynamic (i.e. its temperatures are closely aligned to those obtained by primary thermometers)
- Was simple to realise – i.e. uses practical thermometers ("cheap", fast, easy to use)
- Was reproducible and convenient (i.e. *recipe* based rather than fundamental)
- …and through simple conversion factors could be linked to the earlier scales

International Temperature Scales

1. Precursors:

   Normal hydrogen scale (1887)

   Platinum Resistance Thermometer

2. The defined scales ITS-27…. to…. ITS-90

International Temperature Scales

1. Precursors:

Normal hydrogen scale (1887)

Platinum Resistance Thermometer

Defined temperature scales

- Foundations of how to establish an internationally agreed defined scale were laid by:
- Chappuis in the 1880s at the BIPM in Paris. His work led, in 1887, to the first practical international temperature scale, *the constant-volume (normal) hydrogen scale* based on ice (0 ºC) and steam (100 ºC) fixed points – “Tonnelot” mercury-in-glass thermometers “carried” the scale
- But mercury-in-glass thermometers were not suitable as wide temperature range “scale carriers”

Defined temperature scales

H. L. Callendar
1863 -1930

- Callendar (building on ideas by Siemens 1871) showed that thermometers based on electrical resistance of platinum wire were a practical and convenient way of comparing (*and hence for disseminating*) scales
- So to set up a scale *just (!)* need to measure the resistance of platinum at a number of fixed points of known temperature
- Callendar made a proposal as early as 1899 to establish a defined scale using PRTs calibrated at the freezing point of water and the boiling points of water and sulphur

International Temperature Scales

2. The defined scales ITS-27…. to…. ITS-90

Defined international temperature scales

- Leading to the first defined scale, the International Temperature Scale of 1927 the **ITS-27**
- With ranges:
  - -190 ºC to 660 ºC (Platinum Resistance Thermometer),
  - 660 ºC to 1063 ºC [the then gold freezing point] (thermocouple based on Pt and Pt-Rh alloy [known as type S])
  - Above 1063 ºC optical pyrometry (measurement of “thermal radiation”)

Defined international temperature scales

- Have undergone various revisions:
- ITS-48 (better fixed-point values, adjustment in ranges, modified to include water triple point)
- IPTS-68 (P=practical) (major extension to low temperatures)
- ITS-90 (removed type S thermocouple)
- PLTS-2000 (P=provisional, 0.9 mK to 1 K)

- With the temperatures of the *defined* scales increasingly converging on *thermodynamic* temperature values
- More information can be found on: http://www.bipm.org/en/measurement-units/history-si/temperature-scales/

The ITS-90

standard platinum resistance thermometer [practical thermometer]

The purpose of the International Temperature Scale of 1990 is to define procedures by which certain practical thermometers can be calibrated (using defined fixed points egs water triple point, metal freezing points) that the values of temperature obtained from them are precise and reproducible and *approximate to thermodynamic temperatures as closely as possible*.

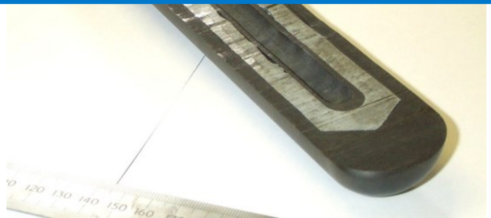
Section through a Metal fixed point

The ITS-90

standard platinum
resistance thermometer
[practical thermometer]

The purpose of the International Temperature Scale of 1990 is to

A purpose unchanged since the first temperature scale in 1927!



Section through a
Metal fixed point

Summary of talk

- Historical introduction to thermometry
- Emergence of primary thermometry and linkage to “practical” temperature scales
- International Temperature Scales

We have come a long way…. what will the next 100 years hold?

ANY QUESTIONS?

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International Temperature Scales

1. Precursor: Normal hydrogen scale (1887)