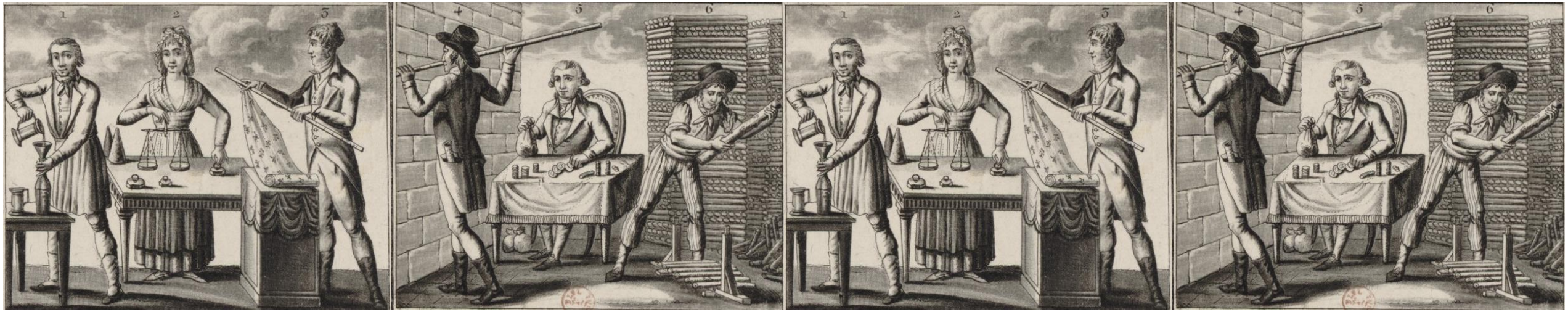

Evolution of the SI

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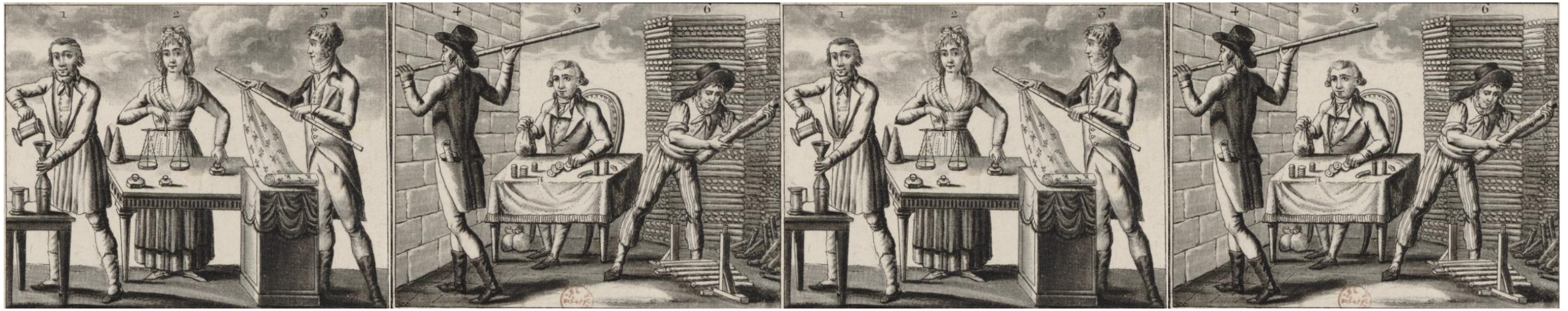
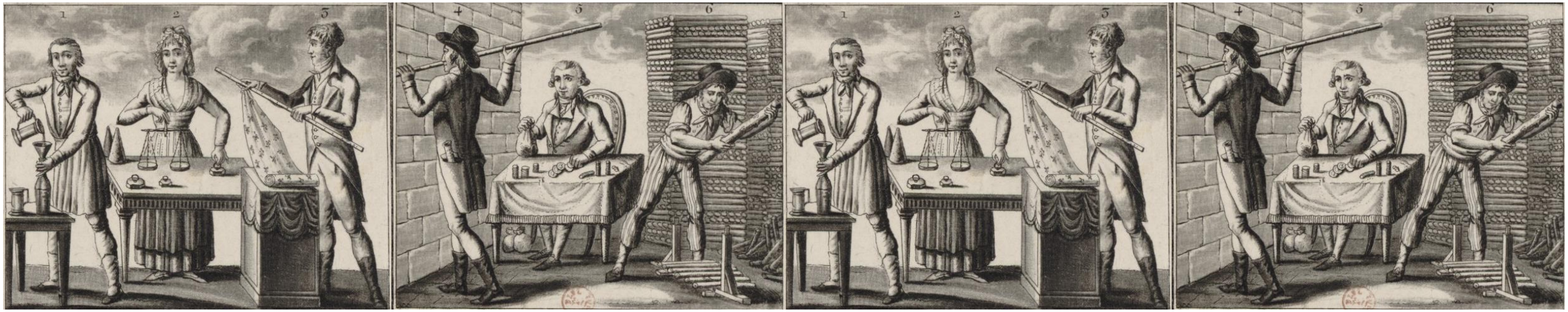
Content

- Science & Measurement
- Situation before the Metre Convention
- The Metre Convention and the SI
- The SI Base Units before CGPM-26
- The SI 2019
- Importance of the SI
- Challenges ahead



Why do we need to know the SI?



- It would help us to understand significance of the SI and appreciate it properly.
- It would help us to understand significance of what has happened since November last year.

Prologue

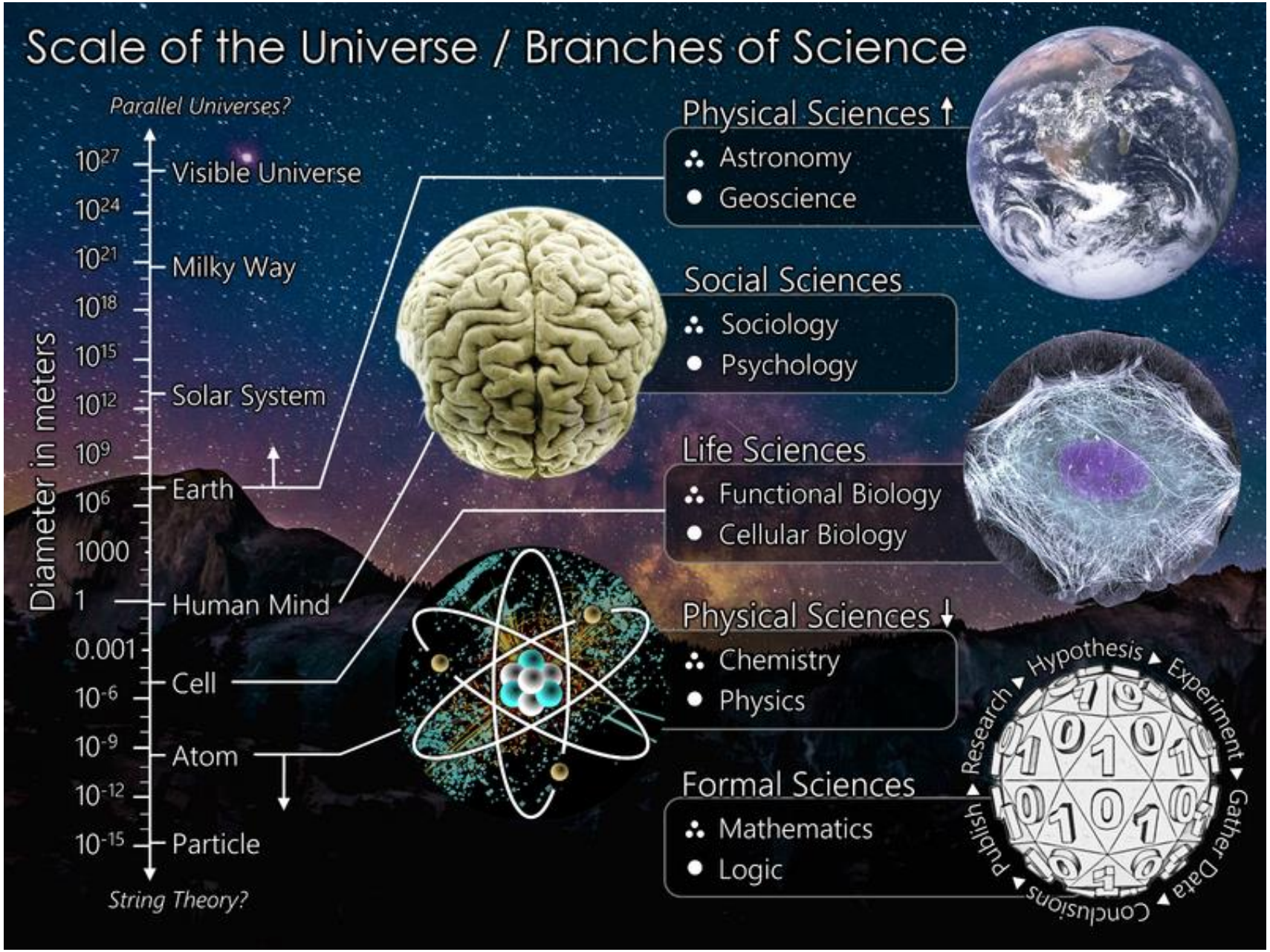
One of the great **under-appreciated stories** of our growth in knowledge as a species is that of our development, in modern history, of **a standardised mathematical language of measurement**: the International System of Units, also known as the SI.

Taken from a website of Glasgow students: the-gist.org

THE GIST — THE GLASGOW INSIGHT INTO SCIENCE AND TECHNOLOGY

Science

- Science, from Latin scientia, means “knowledge”
- Systematic enterprise that builds and organises knowledge in the form of testable explanations and predictions about the universe
- Over centuries, “science” became increasingly associated with what is today known as the “scientific method”, a structured way to study the natural world



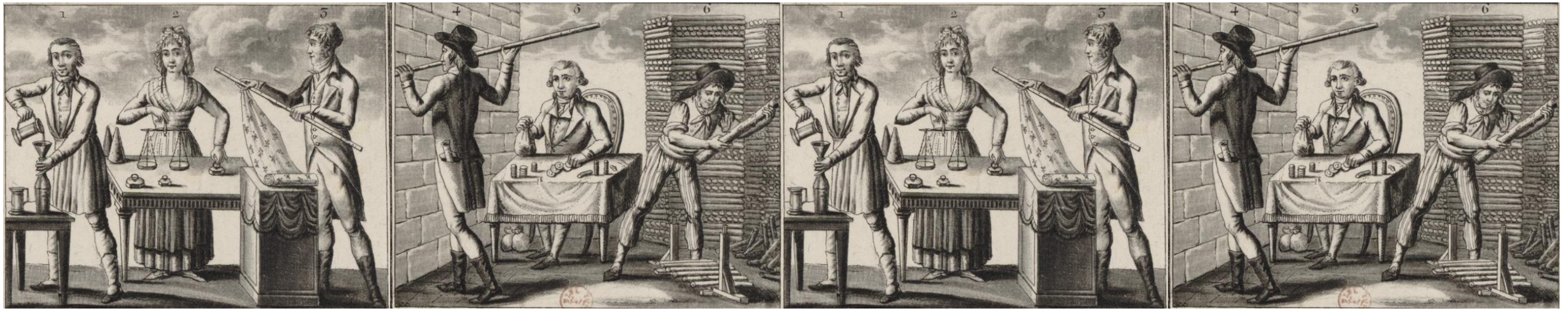
https://en.wikipedia.org/wiki/File:The_Scientific_Universe.png

Measurement

- VIM: process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity
  - NOTE 1 Measurement does not apply to nominal properties.
  - NOTE 2 Measurement implies comparison of quantities or counting of entities.
- Wikipedia: the assignment of a number to a characteristic of an object or event, which can be compared with other objects or events.

Measurement

- Measurement is a cornerstone of trade, science, technology, and quantitative research in many disciplines.



Situation before the Metre Convention

France before the 18th century

- No unified measurement system
- In spite of the attempts of Charlemagne and many kings after him, aiming to reduce the number of existing measurements, France was one of the most inventive and most chaotic countries in this area
- In 1795, there were over seven hundred different units of measure in France
- Volume and length measurements were totally unrelated

A dream: Universal measure

- With the increasing scientific activity of the 17th century came calls for the institution of a "universal measure" (John Wilkins) or "metro cattolico" (Tito Livio Burattini), which would be based on natural phenomena rather than royal decree, and would also be decimal rather than using the various systems of subdivision, often duodecimal, which coexisted at the time

Wilkins, John (1668), *An Essay Towards a Real Character, And a Philosophical Language*, London, UK: Gillibrand

A proposal of redefinition: an example

- Wilkins' idea was to choose the length of a "seconds pendulum" as the unit of length (a pendulum with a half-period of one second)
- Pendulums had recently been demonstrated by Christiaan Huygens
- Their length is quite close to one modern metre (as well as to some other length units which were then in use, such as the yard)
- However, it was soon discovered that the length of a seconds pendulum varies from place to place: French astronomer Jean Richer had measured the 0.3% difference in length between Cayenne (in French Guiana) and Paris.

A universal measure: the metre

- On 16 February 1791, a commission was set up to bring in a uniform system of measurement, following a proposal by the Chevalier JC de Borda - the inventor of the pendulum
- The commission, composed of Borda, Condorcet, Laplace, Lagrange and Monge was faced with a choice between three possible references:
  - the length of a simple pendulum beating at a rate of one second at a latitude of 45°
  - the length of one quarter of the equator
  - the distance from the North pole to the equator, a quarter meridian

Universality – Condorcet's dream (1775)

- Intention was to produce an invariable measure by comparison with a standard borrowed from a natural phenomenon, the universal standard, which would not be based on any national vanity and which could be used by all foreign nations.
- Introduced on 26 March 1791, the metre was defined as being equal to the ten millionth part of one quarter of the terrestrial meridian.
- The metre materialised the idea of a "unit which in its determination was neither arbitrary nor related to any particular nation on the globe"

Determine length of the meridian

- The mission: determination of the exact length of the meridian
- The geodesists in charge of the mission: Pierre-François MECHAIN (1744-1804) and Jean-Baptiste DELAMBRE (1747-1822)
- The work: lasted almost seven years
- The work: Dunkirk to Barcelona

Decimal metric system

- The system of units based on the metre
- The decimal metric system was introduced on 18 germinal year III (7 April 1795) by the law “on weights and measures”
- Decimalisation also brought a real revolution in the calculation of areas and volumes
- Officially adopted in France on 19 frimaire An VIII (10 December 1799) and became the sole legal system of weights and measures from 1801

Units

- Once the base unit of measure had been determined, all that had to be done now was “just” establish all the other resulting units of measure: the square metre and the cubic metre, the litre, the gram, etc
- To determine the unit of mass, the commission preferred water to any other body such as mercury or gold, due to the “ease of obtaining water and distilling it …”
- The kilogram was defined as being equal to the mass of a cubic decimetre of water at a given temperature

Practicality

- For everyday use, the first standards of the metre and the kilogram were manufactured in 1799 and deposited in the Archives of the Republic, dedicated to “all men and all times”
- Both simple and universal, the decimal metric system started to spread outside France
  - Development of railways
  - Growth of industry and the increasing number of exchanges all required accurate units of measure
- Adopted at the start of the 19th century in several Italian provinces, the metric system became compulsory in the Netherlands from 1816 and was chosen by Spain in 1849

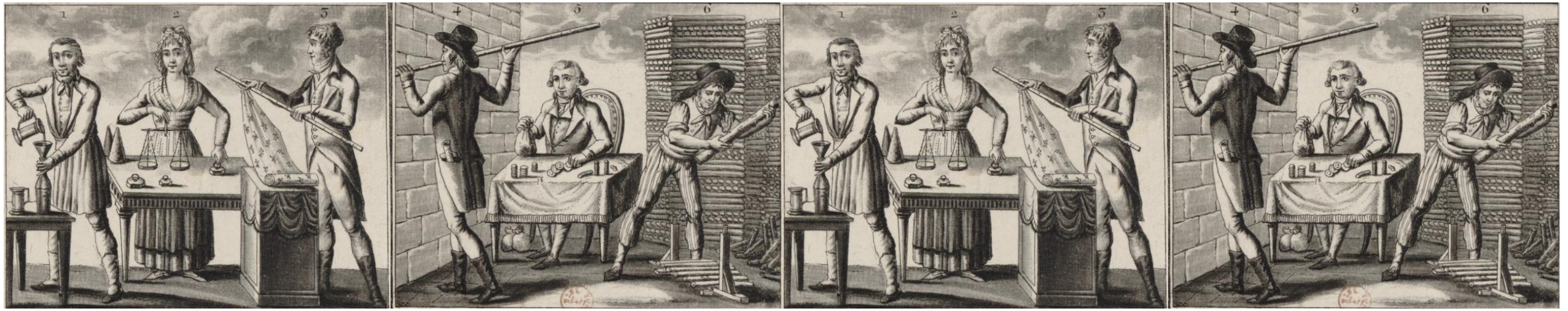
Definitions of the metre since 1798

Basis of definition	Date	Absolute uncertainty	Relative uncertainty
1/10,000,000 part of one half of a meridian, measurement by Delambre and Méchain	1798	0.5–0.1 mm	10^{-4}
First prototype *Mètre des Archives* platinum bar standard	1799	0.05–0.01 mm	10^{-5}
Platinum-iridium bar at melting point of ice (1st CGPM)	1889	0.2–0.1 μm	10^{-7}
Platinum-iridium bar at melting point of ice, atmospheric pressure, supported by two rollers (7th CGPM)	1927	n.a.	n.a.
1,650,763.73 wavelengths of light from a specified transition in krypton-86 (11th CGPM)	1960	0.01–0.005 μm	10^{-8}
Length of the path travelled by light in a vacuum in 1/299,792,458 of a second (17th CGPM)	1983	0.1 nm	10^{-10}

Source gallica.bnf.fr / Bibliothèque nationale de France

Woodcut, dated 1800, illustrates the new decimal units which became the legal norm in France on 4 November 1800, five years after the Metric system was first introduced.

- the litre
- the gram
- the metre
- the are (100 square metres)
- the franc
- the stère (1 cubic metre of wood)



The Metre Convention & the SI

Decimal metric system and Gauss

- 1795 – Louis XVI, then Napoleon: decimal metric system Commission (Lavoisier, Lagrange, Delambre)
- 1799 – Deposition of platinum prototype metre and kilogram in the Archives de la République in Paris
- 1832 – Gauss promoted the application of this metric system. Added the second, defined in astronomy, as a coherent system of units for the physical sciences.
  - Gauss was the first to make absolute measurements of the Earth's magnetic field in terms of a decimal system based on the three mechanical units millimetre, gram, and second. In later years, Gauss and Weber extended these measurements to include other electrical phenomena.

Physics, BAAS and Convention du Mètre

- 1860s – Further development in applications in the field of electricity and magnetism under the active leadership of Maxwell and Thomson through the British Association for the Advancement of Science (BAAS). They formulated the requirement for a coherent system of units with base units and derived units.
- 1874 – BAAS introduced the CGS system, a three-dimensional coherent unit system, using prefixes ranging from micro to mega to express decimal submultiples and multiples.
  - The subsequent development of physics as an experimental science was largely based on this system.
- 1875 – The signing of the Convention du Mètre on 20 May, led to creation of BIPM, establishment of CIPM and CGPM and started construction of new international prototypes of metre and kilogram

CGS, MKS & Internaltional Prototypes

- 1880s - The sizes of the coherent CGS units in the fields of electricity and magnetism proved to be inconvenient. BAAS and the International Electrical Congress (IEC) approved a mutually coherent set of practical units. Among them were the ohm for electrical resistance, the volt for electromotive force, and the ampere for electric current.
- 1885 – First Pt/Ir International Prototype of kilogram was manufactured and kept at the BIPM
- 1889 – The 1st CGPM sanctioned the International Prototypes for the metre and the kilogram.
  - Together with the astronomical second as the unit of time, these units constituted a three-dimensional mechanical unit system similar to the CGS system, but with the base units metre, kilogram, and second, the MKS system.

V, A or Ω

- 1901 – Giovanni Giorgi, Italian scientist and engineer, observed that m, kg, s, and one of V, A, Ω can form a single coherent four-dimensional system
- 1921 – The 6th CGPM extended scope and responsibilities of the BIPM to other fields in physics
- 1927 – The 7th CGPM created the Consultative Committee for Electricity (CCE)
  - The Giorgi proposal was thoroughly discussed by IEC, IUPAP, and other international organisations
- 1939 – CCE proposed the adoption of a four-dimensional system based on the metre, kilogram, second, and ampere
- 1946 – CIPM approved the proposal
- 1948 – BIPM began an international enquiry

The 9th CGPM (1948, Resolution 6)

- Instructed the CIPM:
  - to study the establishment of a complete set of rules for units of measurement
  - to find out for this purpose, by official enquiry, the opinion prevailing in scientific, technical and educational circles in all countries
  - to make recommendations on the establishment of a *practical system of units of measurement* suitable for adoption by all signatories to the *Metre Convention*
- Also laid down general principles for the writing of unit symbols and listed some coherent derived units that were assigned special names.

SI Base Units: m, kg, s, A, K, cd, mol

- 1954 – The 10th CGPM (Resolution 6) adopted as base quantities and units for the practical system the following six quantities: length, mass, time, electric current, thermodynamic temperature and luminous intensity, as well as the six corresponding base units: metre, kilogram, second, ampere, kelvin and candela.
- 1960 – The 11th CGPM gave a name "Système Internationale des Unités" to the system of units << m, kg, s, A, K, cd >>
  - ratified the CIPM 1956 definition of the second & redefined the metre in terms of krypton 86 radiation
- 1971 – The 14th CGPM added the mole as the base unit for amount of substance to make seven base units, after a lengthy discussion between physicists and chemists

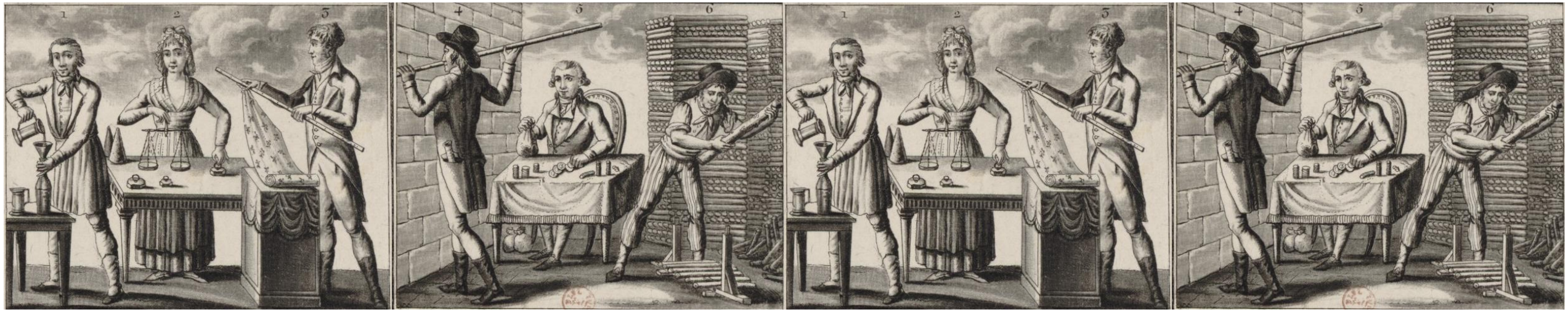
Observation: Development of a system of units, such as the SI, took about 200 years – 1790s to 1970s

1964 – 1967 – 1971 s, A, K, cd, mol

- 12th CGPM (1964) empowers CIPM to investigate atomic and molecular frequency standards
- CIPM declares the caesium 133 hyperfine transition to be the recommended standard
- 13th CGPM (1967/68):
- defines the second in terms of the caesium transition
- CCDS, 1970: defines International Atomic Time, TAI 171
- 14th CGPM, 1971: requests the CIPM to define and establish 171
- International Atomic Time, TAI
- 15th CGPM, 1975: endorses the use of Coordinated Universal Time, UTC

Establish a system of units

- Establish a system of quantities and a set of equations defining the relations between those quantities
  - This is necessary because the equations between the quantities determine the equations relating the units
- Choose definitions for a small number of units, base units,
  - Define units for all other quantities as products of powers of the base units



The SI Base Units before CGPM-26

Metre
Kilogram
Second
Ampere
Kelvin
Candela
mole

Metre – Unit of length

- The 1st CGPM (1889) “The Prototype of the metre chosen by the CIPM. This prototype, at the temperature of melting ice, shall henceforth represent the metric unit of length”
- The 7th CGPM (1927) defined & declared the use of the prototype metre
  - The unit of length is the metre, defined by the distance, at 0°, between the axes of the two central lines marked on the bar of platinum-iridium kept at BIPM and declared Prototype of the metre by the 1st CGPM, this bar being subject to standard atmospheric pressure and supported on two cylinders of at least one centimetre diameter, symmetrically placed in the same horizontal plane at a distance of 571 mm from each other.

Metre – Unit of length

- The 11th CGPM (1960) replaced this definition by another definition based on the wavelength of krypton-86 radiation
  - The metre is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom.
  - This change was adopted in order to improve the accuracy with which the definition of the metre could be realised
  - The realisation being achieved using an interferometer with a travelling microscope to measure the optical path difference as the fringes were counted

The international Prototype of the metre sanctioned by the 1st CGPM in 1889 shall be kept at the BIPM under the conditions specified in 1889.

Metre – Unit of length

- The 15th CGPM (1975) recommended value for the speed of light
  - the speed of propagation of electromagnetic waves in vacuum c = 299 792 458 metres per second
- The 17th CGPM (1983) redefined of the metre using the speed of light
  - The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second

Length, mass & volume???

- The 3rd CGPM (1901)
  Unit of volume, for high accuracy determinations, is the volume occupied by a mass of 1 kilogram of pure water, at its maximum density and at standard atmospheric pressure: this volume is called “litre”.

Kilogram: Unit of mass

- The 1st CGPM (1889) “The Prototype of the kilogram adopted by the CIPM. This prototype shall henceforth be considered as the unit of mass”
- The 3rd CGPM (1901) gave a declaration intended to end the use of the word “weight”, confirmed that: The kilogram is the unit of mass) it is equal to the mass of the international prototype of the kilogram.

Kilogram: Unit of mass

- The 21st CGPM (1999) future redefinition of the kilogram
- The 23rd CGPM (2007) possible redefinition of certain base units of the International System of Units (SI)
- The 24th CGPM (2011) possible future revision of the SI
- The 25th CGPM (2014) future revision of the SI
- The 26th CGPM (2018) revision of the SI

Second: Unit of time

- The 10th CGPM, 1954: second adopted as a base unit
- CIPM 1956 – The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time. [Ratified by The 11th CGPM (1960)]
- CIPM 1964 – CIPM, empowered by Resolution 5 of the 12th CGPM (1964), declared that the transition between the hyperfine levels F = 4, M = 0 and F = 3, M = 0 of the ground state $2S_{1/2}$ of the caesium 133 atom, unperturbed by external fields, to be the recommended standard and that the frequency of this transition is assigned the value 9 192 631 770 hertz.

Second: Unit of time

- The 13th CGPM (1967/68) defined the second in terms of the caesium transition

  “The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom”
- CCDS (1970) defined International Atomic Time, TAI
- The 14th CGPM (1971) requested the CIPM to define and establish International Atomic Time, TAI
- The 15th CGPM (1975) endorsed the use of Coordinated Universal Time, UTC
- The 24th CGPM (2011) possible future revision of the SI
- The 26th CGPM (2018) revision of the SI

Ampere: Unit of electrical current

- CIPM (1946) definitions of coherent electrical units in the metre-kilogram-second (MKS) system of units (to enter into force on 1 January 1948)
- The 10th CGPM (1954) ampere adopted as a base unit
- The 14th CGPM (1971) adopts the name siemens, symbol S, for electrical conductance
- The 18th CGPM (1987) forthcoming adjustment to the representations of the volt and of the ohm
- CIPM (1988) defined
  - conventional value of the Josephson constant (to enter into force on 1 January 1990)
  - conventional value of the von Klitzing constant (to enter into force on 1 January 1990)
- The 23rd CGPM (2007) possible redefinition of certain base units of the SI
- The 24th CGPM (2011) possible future revision of the SI
- The 25th CGPM (2014) future revision of the SI
- The 26th CGPM (2018) revision of the SI

Kelvin: Unit of thermodynamic temperature

- The 9th CGPM (1948) adopts the triple point of water as the thermodynamic reference point, adopts the zero of Celsius temperature to be 0.01 degree below the triple point
- The CIPM (1948) adopts the name degree Celsius for the Celsius temperature scale
- The 10th CGPM (1954) defines thermodynamic temperature such that the triple point of water is 273.16 degrees Kelvin exactly, defines standard atmosphere
- The 10th CGPM (1954) degree Kelvin adopted as a base unit
- The 13th CGPM (1967/68) decides formal definition of the kelvin, symbol K
- The CIPM (1989) the International Temperature Scale of 1990, ITS-90
- The CIPM (2005) note added to the definition of the kelvin concerning the isotopic composition of water
- The 23rd CGPM (2007) clarification of the definition of the kelvin, unit of thermodynamic temperature
- The 23rd CGPM (2007) possible redefinition of certain base units of the SI
- The 24th CGPM (2011) possible future revision of the SI
- The 25th CGPM (2014) future revision of the SI
- The 26th CGPM (2018) revision of the SI

Mole: Unit of Amount of substance

- The 14th CGPM (1971) definition of the mole, symbol mol, as a seventh base unit, and rules for its use

  The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is “mol”
- The 21st CGPM (1999) adopts the special name katal, kat (catalytic activity, especially in the fields of medicine and biochemistry)
- The 23rd CGPM (2007) on the possible redefinition of certain base units of the SI
- The 24th CGPM (2011) possible future revision of the SI
- The 25th CGPM (2014) future revision of the SI
- The 26th CGPM (2018) revision of the SI

Candela: Unit of luminous intensity

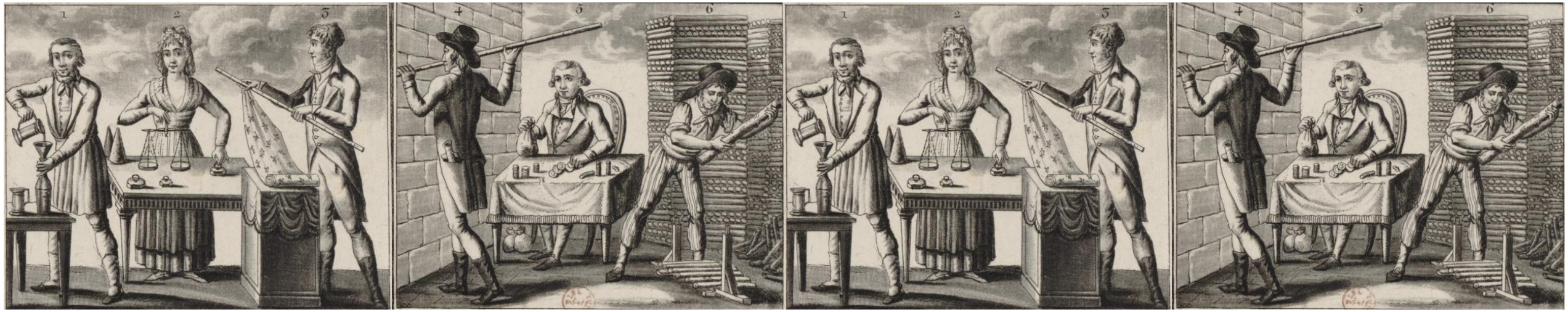
- CIPM (1946) definition of photometric units, new candle and new lumen (to enter into force on 1 January 1948)
- The 10th CGPM (1954) candela adopted as a base unit
- The 13th CGPM (1967/68) defines the candela, symbol cd, in terms of a black body radiator

  "The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre."
- The 16th CGPM (1979) redefines the candela in terms of monochromatic radiation

  "The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian"
- The 24th CGPM (2011) possible future revision of the SI
- The 26th CGPM (2018) revision of the SI

metre	The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.
kilogram	The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.
second	The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.
ampere	The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.

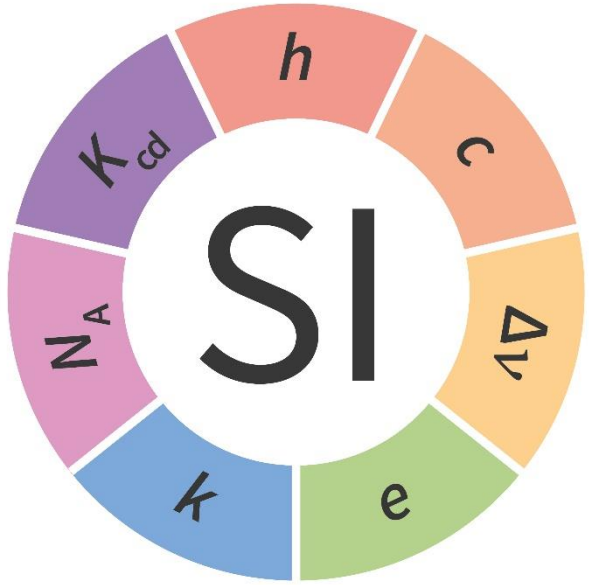
kelvin	The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
mole	The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is “mol”.
candela	The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.



The SI: 2019

The SI until 20 May 2019

Transition



The SI from 20 May 2019

The International System of Units, the SI, is the system of units in which

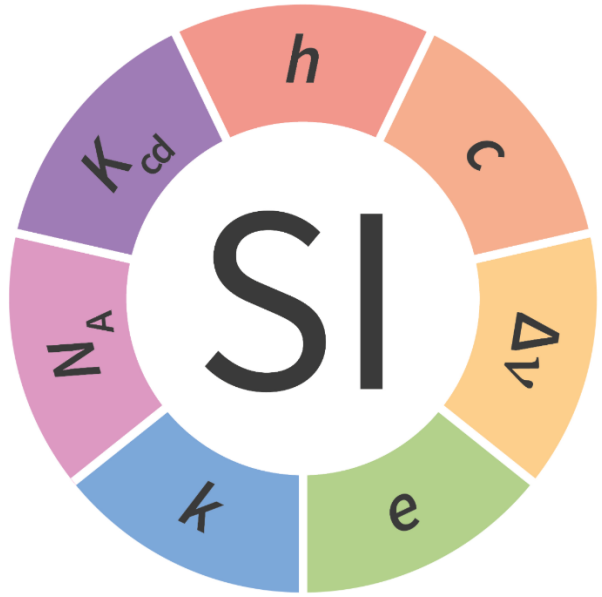
- the unperturbed ground state hyperfine transition frequency of the caesium 133 atom Cs is 9 192 631 770 Hz,
- the speed of light in vacuum c is 299 792 458 m/s,
- the Planck constant h is 6.626 070 15 x 10^{-34} J s,
- the elementary charge e is 1.602 176 634 x 10^{-19} C,
- the Boltzmann constant k is 1.380 649 x 10^{-23} J/K,
- the Avogadro constant N_A is 6.022 140 76 x 10^{23} mol^{-1},
- the luminous efficacy of monochromatic radiation of frequency 540 x 10^{12} Hz, K_{cd}, is 683 lm/W.

The International System of Units (SI)

→ The definition of the SI units is established in terms of a set of seven defining constants. The complete system of units can be derived from the fixed values of these defining constants, expressed in the units of the SI. These seven defining constants are the most fundamental feature of the definition of the entire system of units.

The seven defining constants of the SI and the seven corresponding units they define:

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	m s^{-1}
Planck constant	h	6.626 070 15 x 10^{-34}	J s
elementary charge	e	1.602 176 634 x 10^{-19}	C
Boltzmann constant	k	1.380 649 x 10^{-23}	J K^{-1}
Avogadro constant	N_A	6.022 140 76 x 10^{23}	mol^{-1}
luminous efficacy	K_{cd}	683	lm W^{-1}



These particular constants were chosen after having been identified as being the best choice, taking into account the previous definition of the SI, which was based on seven base units, and progress in science.

Quantity	SI unit
time	The **second**, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.
length	The **metre**, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299 792 458 when expressed in the unit m s^{-1}, where the second is defined in terms of $\Delta\nu_{Cs}$.
mass	The **kilogram**, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.626\ 070\ 15 \times 10^{-34}$ when expressed in the unit J s, which is equal to kg m^2 s^{-1}, where the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$.
electric current	The **ampere**, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be $1.602\ 176\ 634 \times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.
thermodynamic temperature	The **kelvin**, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be $1.380\ 649 \times 10^{-23}$ when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.
amount of substance	The **mole**, symbol mol, is the SI unit of amount of substance. One mole contains exactly $6.022\ 140\ 76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number. The amount of substance, symbol n, of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.
luminous intensity	The **candela**, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or cd sr kg^{-1} m^{-2} s^3, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.

The second

The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.

This definition implies the exact relation $\Delta\nu_{Cs}$ = 9 192 631 770 Hz. Inverting this relation gives an expression for the unit second in terms of the defining constant $\Delta\nu_{Cs}$:

$$1\,\mathrm{Hz} = \frac{\Delta\nu_{Cs}}{9\,192\,631\,770}$$

or

$$1\,\mathrm{s} = \frac{9\,192\,631\,770}{\Delta\nu_{Cs}}.$$

The effect of this definition is that the second is equal to the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the unperturbed ground state of the ^{133}Cs atom.

The metre

The metre, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299 792 458 when expressed in the unit m s^{-1}, where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$.

This definition implies the exact relation c = 299 792 458 m s^{-1}. Inverting this relation gives an exact expression for the metre in terms of the defining constants c and $\Delta\nu_{Cs}$:

$$1\,\mathrm{m} = \left(\frac{c}{299\,792\,458}\right)\mathrm{s} = \frac{9\,192\,631\,770}{299\,792\,458}\,\frac{c}{\Delta\nu_{Cs}} \approx 30{,}663\,319\,\frac{c}{\Delta\nu_{Cs}}\,.$$

The effect of this definition is that one metre is the length of the path travelled by light in vacuum during a time interval with duration of 1/299 792 458 of a second.

The kilogram

The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant *h* to be 6.626 070 15 x 10^{-34} when expressed in the unit J s, which is equal to kg m^2 s^{-1}, where the metre and the second are defined in terms of *c* and $\Delta\nu_{Cs}$.

This definition implies the exact relation h = 6.626 070 15 x 10^{-34} kg m^2 s^{-1}. Inverting this relation gives an exact expression for the kilogram in terms of the three defining constants h, $\Delta\nu_{Cs}$ and c:

$$1\,\mathrm{kg} = \left(\frac{h}{6.626\,070\,15\times10^{-34}}\right)\mathrm{m}^{-2}\mathrm{s}$$

which is equal to

$$1\,\mathrm{kg} = \frac{(299\,792\,458)^2}{(6.626\,070\,15\times10^{-34})(9\,192\,631\,770)}\frac{h\,\Delta\nu_{\mathrm{Cs}}}{c^2} \approx 1.475\,5214\times10^{40}\,\frac{h\,\Delta\nu_{\mathrm{Cs}}}{c^2}$$

The effect of this definition is to define the unit kg m^2 s^{-1} (the unit of both the physical quantities action and angular momentum). Together with the definitions of the second and the metre this leads to a definition of the unit of mass expressed in terms of the Planck constant h.

The ampere

The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge *e* to be 1.602 176 634 x 10^{-19} when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.

This definition implies the exact relation *e* = 1.602 176 634 x 10^{-19} A s. Inverting this relation gives an exact expression for the unit ampere in terms of the defining constants *e* and $\Delta\nu_{Cs}$:

$$1\,\mathrm{A} = \left(\frac{e}{1.602\,176\,634 \times 10^{-19}}\right)\mathrm{s}^{-1}$$

which is equal to

$$1\,\mathrm{A} = \frac{1}{(9\,192\,631\,770)\left(1.602\,176\,634 \times 10^{-19}\right)}\Delta\nu_{Cs}e \approx 6.789\,687 \times 10^{8}\,\Delta\nu_{Cs}e$$

The effect of this definition is that one ampere is the electric current corresponding to the flow of 1/(1.602 176 634 x 10^{-19}) elementary charges per second.

The kelvin

The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant *k* to be 1.380 649 x 10^{-23} when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of *h*, *c* and $\Delta\nu_{Cs}$.

This definition implies the exact relation k = 1.380 649 x 10^{-23} kg m^2 s^{-2} K^{-1}. Inverting this relation gives an exact expression for the kelvin in terms of the defining constants k, h and $\Delta\nu_{Cs}$:

$$1\,\mathrm{K} = \left(\frac{1.380\,649}{k}\right) \times 10^{-23}\ \mathrm{kg\ m^2\ s^{-2}}$$

which is equal to

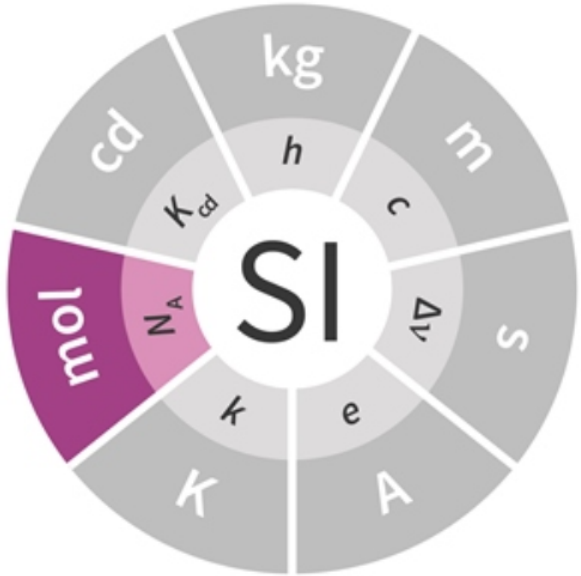
$$1\,\mathrm{K} = \frac{1.380\,649 \times 10^{-23}}{(6.626\,070\,15 \times 10^{-34})(9\,192\,631\,770)} \frac{\Delta\nu_{Cs} h}{k} \approx 2.266\,6653 \frac{\Delta\nu_{Cs} h}{k}$$

The effect of this definition is that one kelvin is equal to the change of thermodynamic temperature that results in a change of thermal energy $k\,T$ by 1.380 649 x 10^{-23} J.

The mole

The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly 6.022 140 76 x 10^{23} elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number.

The amount of substance, symbol *n*, of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.



This definition implies the exact relation N_A = 6.022 140 76 x 10^{23} mol^{-1}. Inverting this relation gives an exact expression for the mole in terms of the defining constant N_A:

$$1\,\text{mol} = \left(\frac{6.022\,140\,76 \times 10^{23}}{N_A} \right)$$

The effect of this definition is that the mole is the amount of substance of a system that contains 6.022 140 76 x 10^{23} specified elementary entities.

The candela

The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540 x 10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or cd sr kg^{-1} m^{-2} s^3, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.

This definition implies the exact relation K_{cd} = 683 cd sr kg^{-1} m^{-2} s^3 for monochromatic radiation of frequency ν = 540 x 10^{12} Hz. Inverting this relation gives an exact expression for the candela in terms of the defining constants K_{cd}, h and $\Delta\nu_{Cs}$:

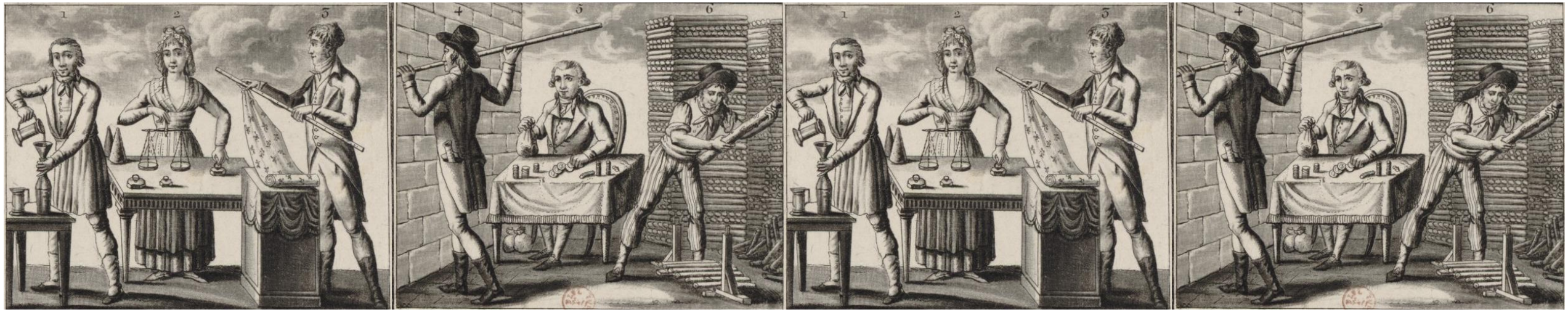
$$1\,\mathrm{cd} = \left(\frac{K_{cd}}{683}\right)\mathrm{kg\ m^2\ s^{-3}\ sr^{-1}}$$

which is equal to

$$1\,\mathrm{cd} = \frac{1}{\left(6.626\,070\,15\times10^{-34}\right)\left(9\,192\,631\,770\right)^2\,683}\,(\Delta\nu_{Cs})^2\ h\ K_{cd}$$

$$\approx 2.614\,830\times10^{10}\ (\Delta\nu_{Cs})^2\ h\ K_{cd}$$

The effect of this definition is that one candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} Hz and has a radiant intensity in that direction of (1/683) W/sr.



Importance of the SI Units

Traceability

Comparability

Reference

Metrological traceability

- Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty

- NOTE 7 The ILAC considers the elements for confirming metrological traceability to be an unbroken metrological traceability chain to an international measurement standard or a national measurement standard, a documented measurement uncertainty, a documented measurement procedure, accredited technical competence, metrological traceability to the SI, and calibration intervals (see ILAC P-10:2002).

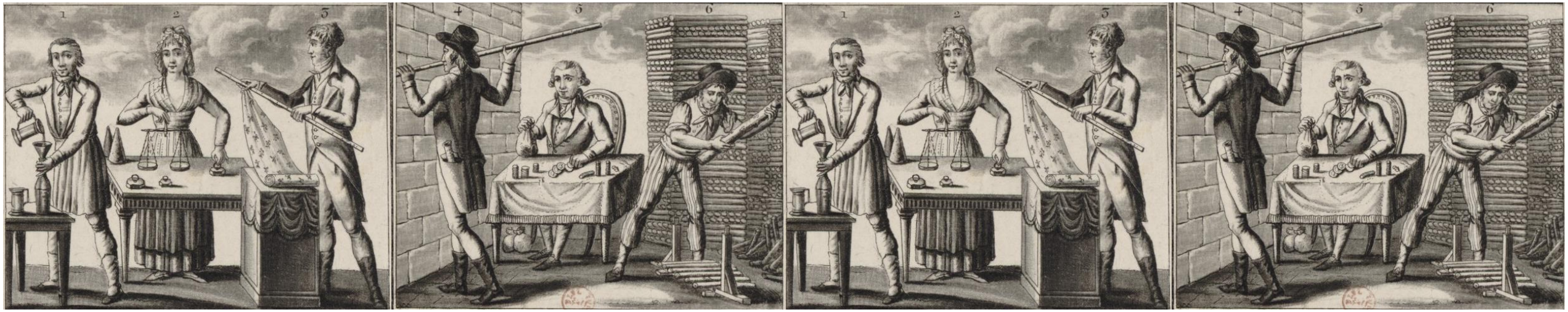
Traceability to a measurement unit

- Metrological traceability where <u>the reference is the definition of a measurement unit</u> through its practical realisation

- NOTE The expression “traceability to the SI” means ‘metrological traceability to a measurement unit of the International System of Units’.

Metrological comparability

- Comparability of measurement results, for quantities of a given kind, that are metrologically traceable to the same reference



Challenge ahead

NMI

- To understand significance of the changes and the revision
- To utilise the changes for the benefit of metrology community, S&T development and the public
  - Improve metrological traceability, national measurement system and measurement uncertainty
  - Further research and development
  - Improve accuracy, stability and reliability of measurement services
- To get more people interested and understand the movement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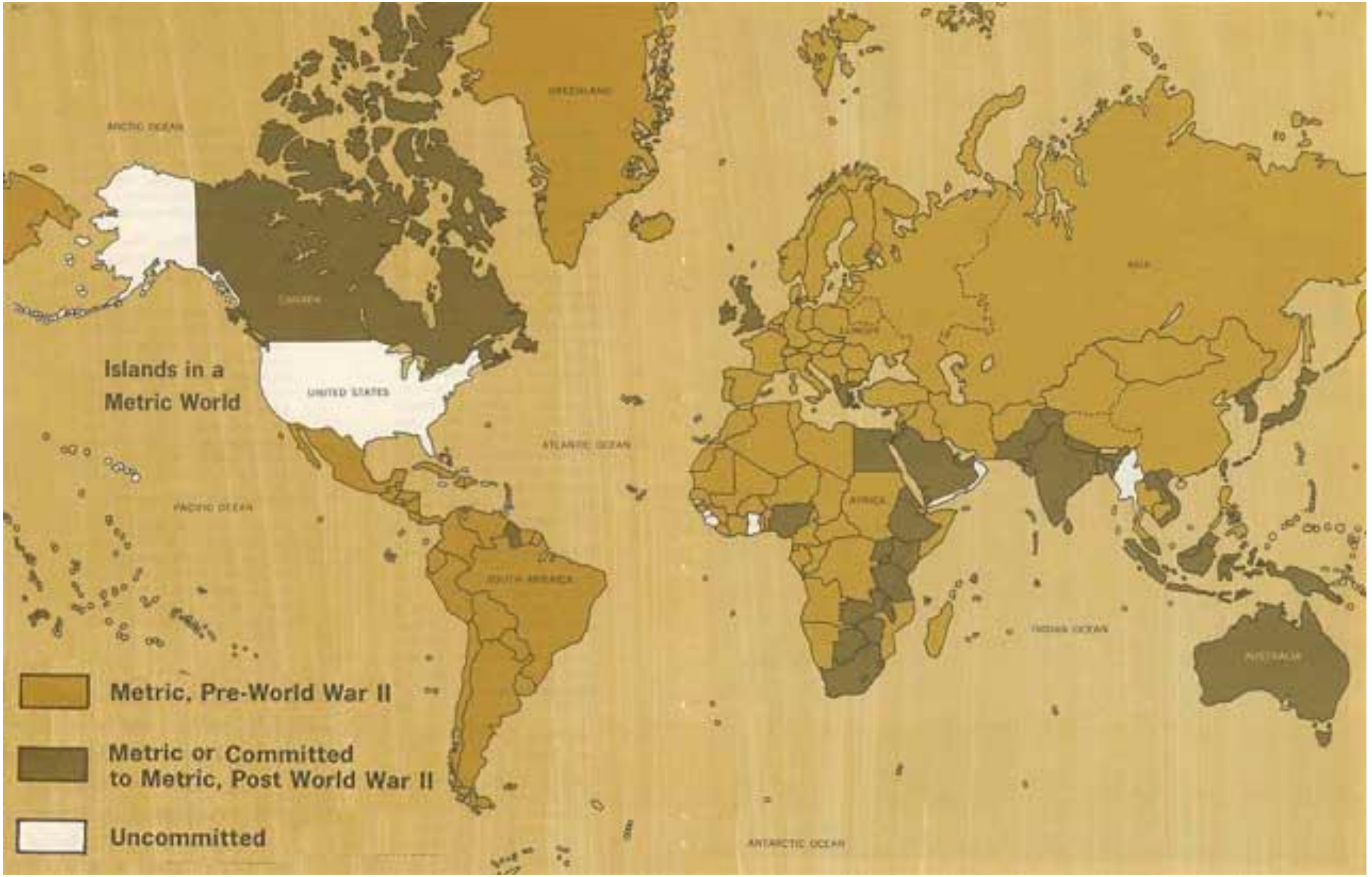
Islands in a
Metric World
GREENLAND
ARCTIC OCEAN
CANADA
UNITED STATES
ATLANTIC OCEAN
PACIFIC OCEAN
SOUTH AMERICA
AFRICA
ASIA
INDIAN OCEAN
AUSTRALIA
ANTARCTIC OCEAN
Metric, Pre-World War II
Metric or Committed
to Metric, Post World War II
Uncommitted


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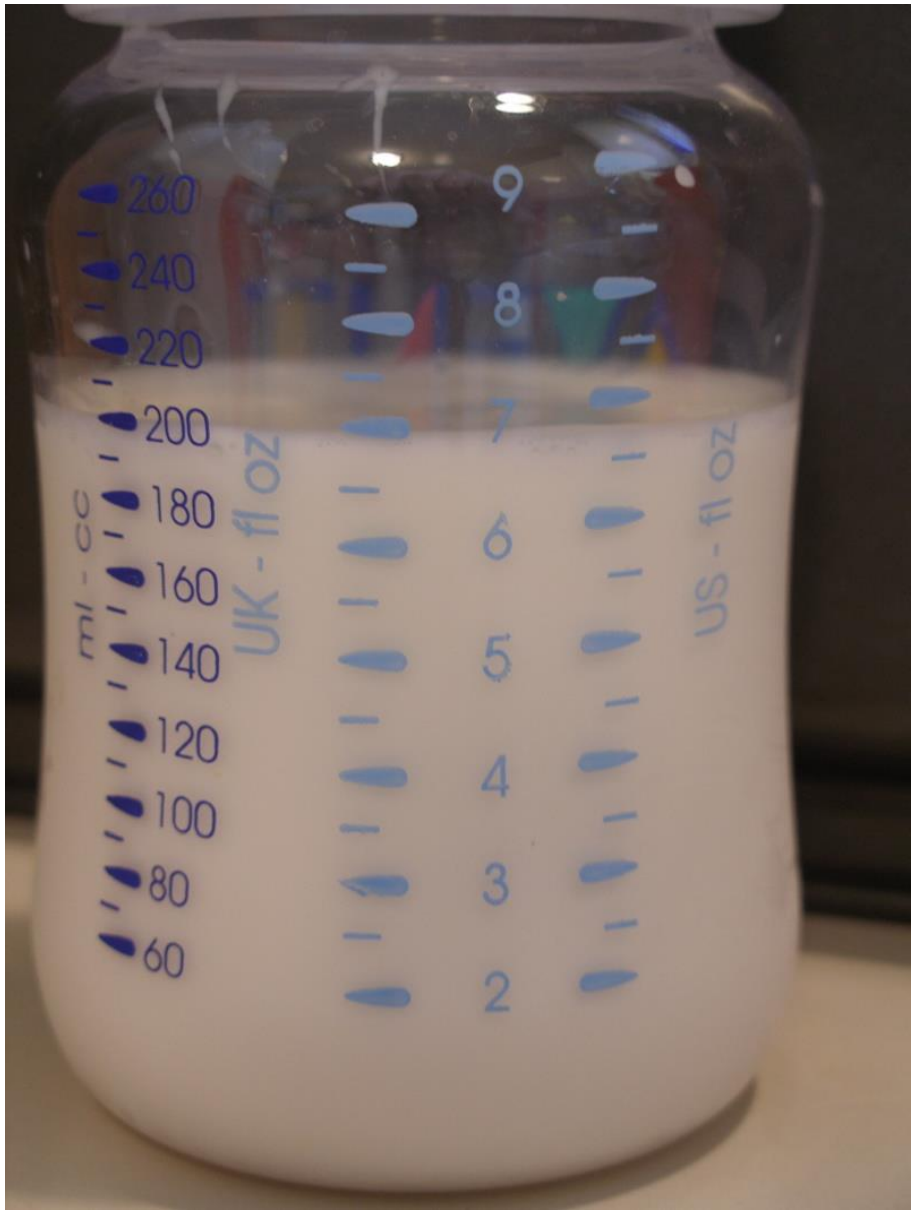
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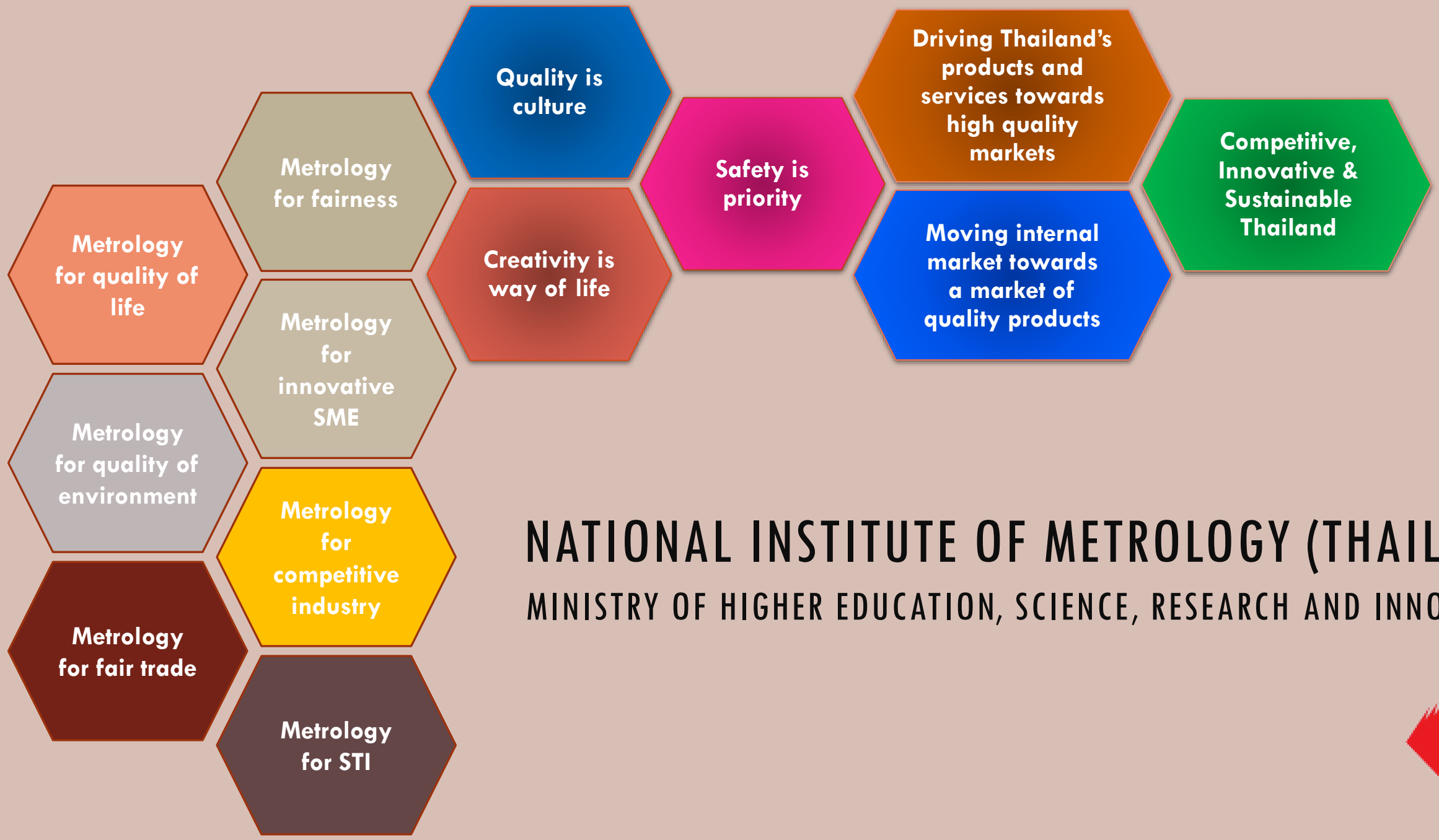

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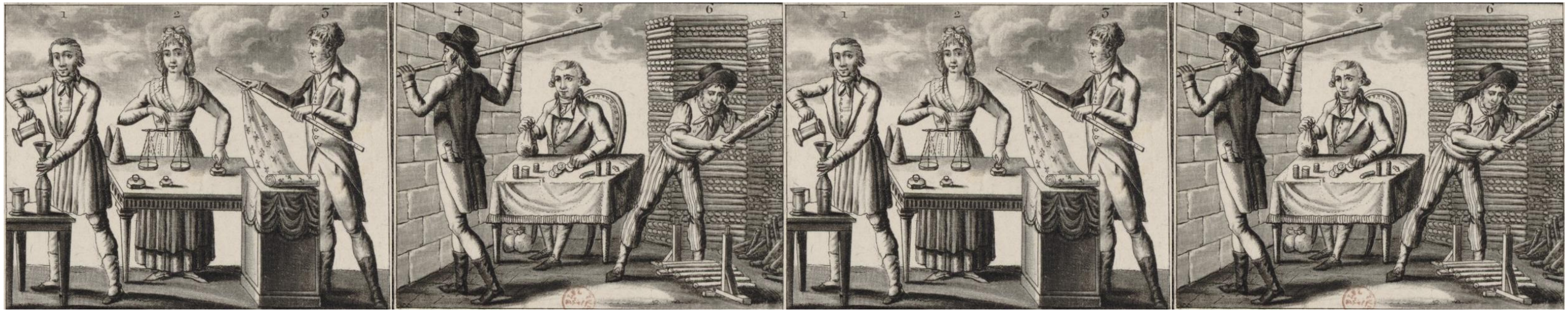

Terms & Definitions

Quantity

- **Quantity**: property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference
- **Base quantity**: quantity in a conventionally chosen subset of a given system of quantities, where no subset quantity can be expressed in terms of the others
- **International System of Quantities**: system of quantities based on the seven base quantities: length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity

Measurement unit

- **Measurement unit**: real scalar quantity, defined and adopted by convention, with which any other quantity of the same kind can be compared to express the ratio of the two quantities as a number
  - NOTE 1 Measurement units are designated by conventionally assigned names and symbols.
- **Base unit**: measurement unit that is adopted by convention for a base quantity
  - NOTE 1 In each coherent system of units, there is only one base unit for each base quantity.
    - EXAMPLE In the SI, the metre is the base unit of length. In the CGS systems, the centimetre is the base unit of length.

It means that

- The value of a quantity is generally expressed as the product of a number and a unit.
- The unit is simply a particular example of the quantity concerned, which is used as a reference, and the number is the ratio of the value of the quantity to the unit.