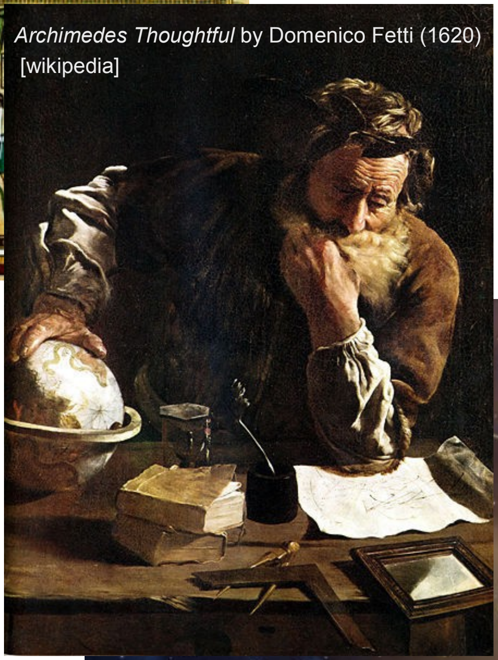
Introduction to Metrology

SI – the international system of units

2 SI – the international system of units

1. System of units: from trade to science
2. Base and derived units
3. Unit realisations and measurement standards

2.1 A system of units: from trade to science



Archimedes Thoughtful by Domenico Fetti (1620) [wikipedia]

SI – system for characterizing physical and chemical phenomena

speed: $v = \frac{\Delta x}{\Delta t}$

force: $F = ma = m\frac{\Delta x}{(\Delta t)^2}$

energy: $E = F\Delta x = \frac{m(\Delta x)^2}{(\Delta t)^2}$

power: $P = \frac{F\Delta x}{\Delta t} = \frac{m(\Delta x)^2}{(\Delta t)^3}$

pressure: $p = \frac{F}{A} = \frac{m\Delta x}{(\Delta t)^2 l^2}$

density: $\rho = \frac{m}{V} = \frac{m}{l^3}$

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2.2 Base and derived units

SI system – properties

- based on a set of 7 base units
  - by convention these are assumed to be independent
- other units are formed as products of powers from base units (derived units)
- some derived units have special names like Newton
- system is coherent i.e.

equations between the numerical values of quantities take exactly the same form as the equations between the quantities themselves

- decimal system is used

SI system – Base units

Base quantity		SI base unit	
Name	Symbol	Name	Symbol
length	l, x, r, etc.	metre	m
mass	m	kilogram	kg
time, duration	t	second	s
electric current	I, i	ampere	A
thermodynamic temperature	T	kelvin	K
amount of substance	n	mole	mol
luminous intensity	I_v	candela	cd

[2.1]

Definitions of base units

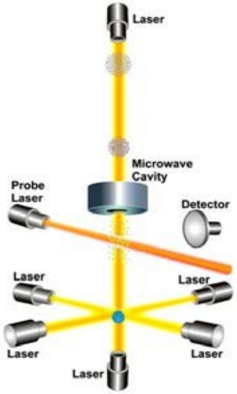
- **Kilogram**:

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

- **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.

- **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.

Need for redefining SI base units

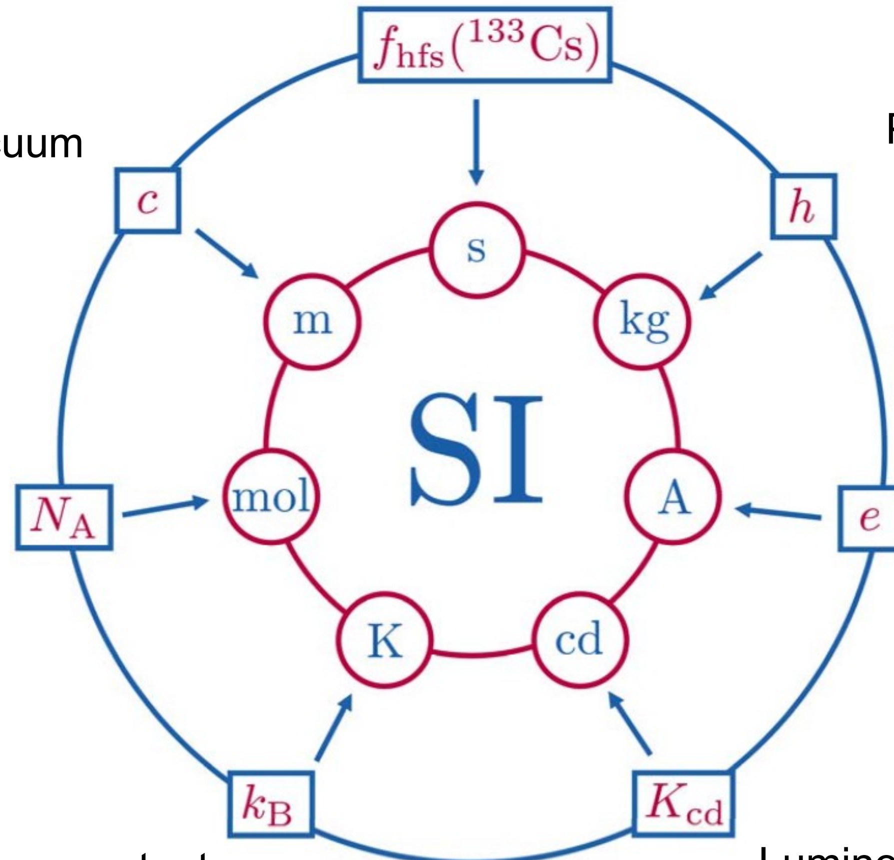
- Drawbacks of the current SI are:
  - Kilogram is defined with an artefact
  - The definition of kelvin is based on material properties
  - The definition of ampere limits the achievable accuracy and is not currently use (quantum standards of ohm and voltage are used instead through the Ohm's law)
- Because of these, drift, non-uniqueness and limitations in accuracy cannot completely be prevented.

SI base units in future

Ground state hyperfine splitting frequency of the caesium 133 atom

Speed of light in vacuum

Planck constant



Avogadro constant

Elementary charge

Boltzmann constant

Luminous efficacy

SI system – Derived units

Derived quantity		SI coherent derived unit	
Name	Symbol	Name	Symbol
area	A	square metre	m^2
volume	V	cubic metre	m^3
speed, velocity	v	metre per second	m/s
acceleration	a	metre per second squared	m/s^2
wavenumber	σ, $\tilde{\nu}$	reciprocal metre	m^{-1}
density, mass density	ρ	kilogram per cubic metre	kg/m^3
surface density	ρ_A	kilogram per square metre	kg/m^2
specific volume	v	cubic metre per kilogram	m^3/kg
current density	j	ampere per square metre	A/m^2
magnetic field strength	H	ampere per metre	A/m
amount concentration [(a)], concentration	c	mole per cubic metre	mol/m^3
mass concentration	ρ, γ	kilogram per cubic metre	kg/m^3
luminance	L_v	candela per square metre	cd/m^2
refractive index [(b)]	n	one	1
relative permeability [(b)]	μ_r	one	1

(*a*) In the field of clinical chemistry this quantity is also called substance concentration.

(*b*) These are dimensionless quantities, or quantities of dimension one, and the symbol “1” for the unit (the number “one”) is generally omitted in specifying the values of dimensionless quantities.

[2.1]

SI system – Derived units with special names

	SI coherent derived unit [(a)]			
Derived quantity	Name	Symbol	Expressed in terms of other SI units	Expressed in terms of SI base units
plane angle	radian [(b)]	rad	1 [(b)]	m/m
solid angle	steradian [(b)]	sr [(c)]	1 [(b)]	m^2/m^2
frequency	hertz [(d)]	Hz		s^{-1}
force	newton	N		$m\ kg\ s^{-2}$
pressure, stress	pascal	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
energy, work, amount of heat	joule	J	N m	$m^2\ kg\ s^{-2}$
power, radiant flux	watt	W	J/s	$m^2\ kg\ s^{-3}$
electric charge, amount of electricity	coulomb	C		s A
electric potential difference, electromotive force	volt	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
capacitance	farad	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
electric resistance	ohm	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
electric conductance	siemens	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$

[2.1]

SI system – Derived units with special names 2

	SI coherent derived unit [a]			
Derived quantity	Name	Symbol	Expressed in terms of other SI units	Expressed in terms of SI base units
magnetic flux	weber	Wb	V s	$m^2\ kg\ s^{-2}\ A^{-1}$
magnetic flux density	tesla	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
inductance	henry	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
Celsius temperature	degree Celsius [e]	°C		K
luminous flux	lumen	lm	cd sr [c]	cd
illuminance	lux	lx	lm/m^2	$m^{-2}\ cd$
activity referred to a radionuclide [f]	becquerel [d]	Bq		s^{-1}
absorbed dose, specific energy (imparted), kerma	gray	Gy	J/kg	$m^2\ s^{-2}$
dose equivalent, ambient dose equivalent, directional dose equivalent, personal dose equivalent	sievert [g]	Sv	J/kg	$m^2\ s^{-2}$
catalytic activity	katal	kat		$s^{-1}\ mol$

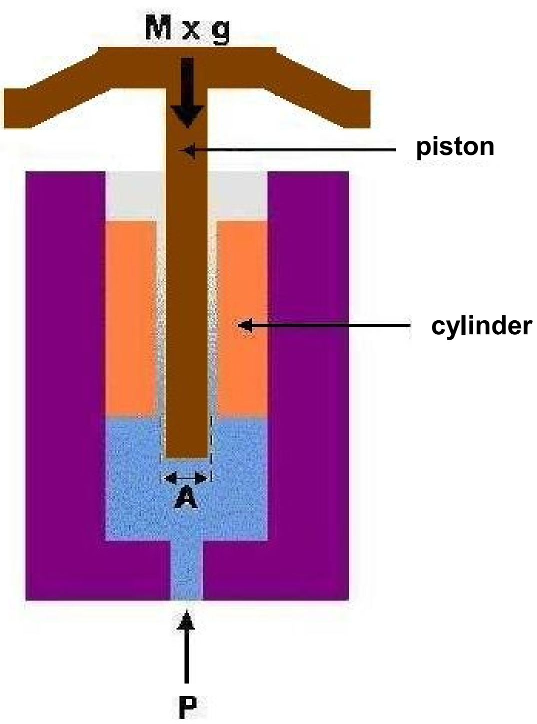
[2.1]

Realisation of a derived unit

- The realisation forms a link between the measurements of a derived quantity and the SI base units.
- Characteristics of the realisation:
  - Based on the definition of the quantity
  - Measurements in terms of SI units (base or derived but not of the same quantity) with traceability to national/international measurement standards
  - Full uncertainty analysis
  - Comparisons to other realisations of the same quantity
- National Standards Laboratories maintain realisations (or secondary standards) for a set of derived quantities

Realisation of the pascal

- Unit with a special name: 1 Pa = 1 m-1 kg s-2



Definition of pressure:

$$p = \frac{F}{A}$$

Realisation of the unit:

Force lifting the piston *F1*:

$$F = pA_1$$

Force lowering the piston *F2*:

$$F2 = mg$$

In equilibrium:

$$F1 = F2 \Rightarrow p = \frac{mg}{A}$$

Pressure balance

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Realisation of the unit of the dew-point temperature (K or °C)

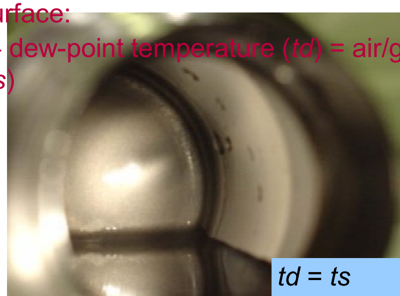
- Same unit as of the temperature but different meaning: Dew-point temperature *(td)*:

The temperature at which the gas would be saturated with respect to a plane surface of pure liquid water or solid ice at the same gas pressure.

A saturator-based primary humidity standard

Air or other gas is saturated with respect to plane water or ice surface:

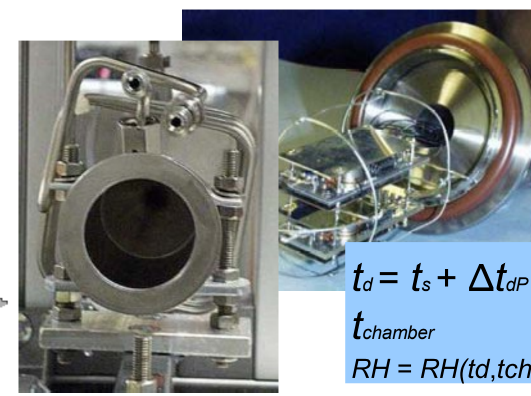
⇒ dew-point temperature (*td*) = air/gas temperature in the saturator (*ts*)



td = *ts*
RH = 100%

Saturated air/gas passes through internally polished stainless steel tubing .

$t_d \approx t_s < t_{tubing}$
RH < 100 %



$t_d = t_s + \Delta t_{dP} < t_{chamber}$
RH = *RH(td,tchamber)*

The air or gas enters a measurement chamber. Humidity in the chamber is determined by the temperatures and pressures of the saturator and the chamber

2.3 Measurement standards and traceability

Traceability in chemical measurements

SI unit: mole

The mole was added to SI in 1971.

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Chemical primary methods

- Isotope Dilution Mass Spectrometry
- Gravimetry
- Titrimetry
- Coulometry
- Freezing Point Depression (Differential Scanning Calorimetry)

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Certified reference materials

ISO Guides 30 – 35, 1989 - 2000

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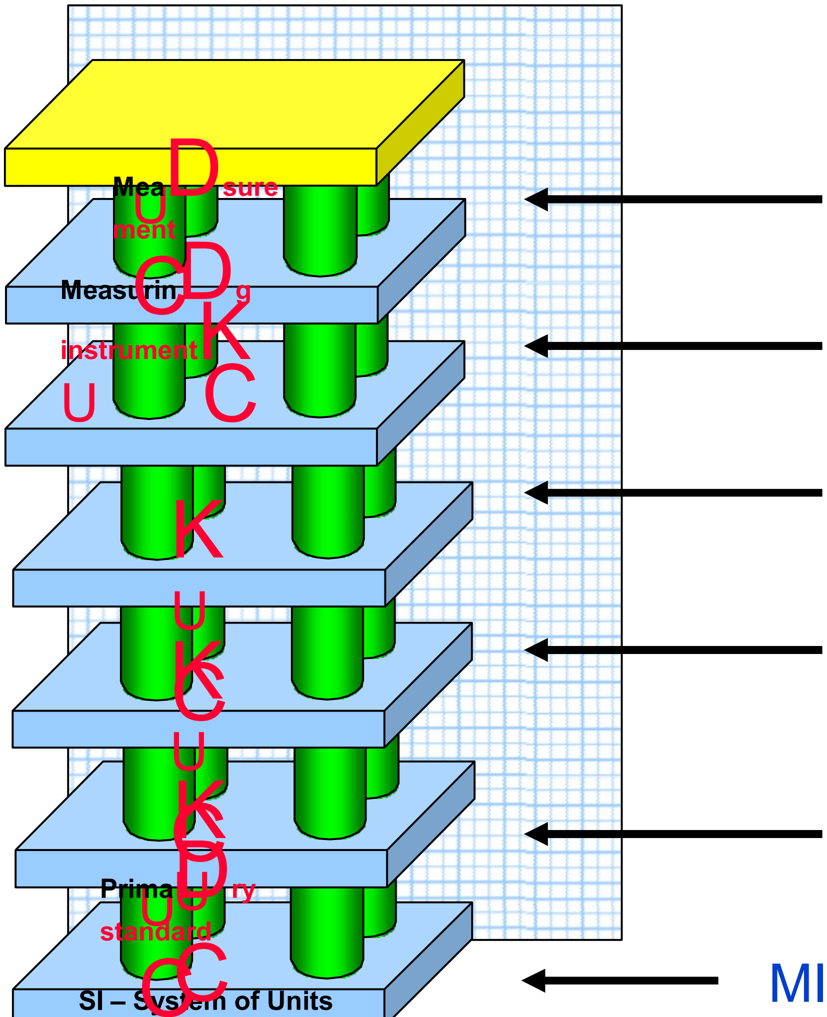
Validated measurement methods and reference materials in laboratories

Traceability to altitude measurements in a military aircraft



Altimeter

±10 m

The pressure simulator of the brigade

±30 Pa ~ ±2.6 m

K013 pressure working standard

±20 Pa ~ ±1.7 m

K013 pressure reference standard

±10 Pa ~ ±0.9 m

MIKES Primary Pressure Standard

MIKES Primary Mass and Length Standards