The definition of the kelvin in the new SI

Michael de Podesta

Varenna 216
6th July2016

Talk#2

How will you know what the temperature is in 2018?

Michael de Podesta

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6th July2016

Talk#2

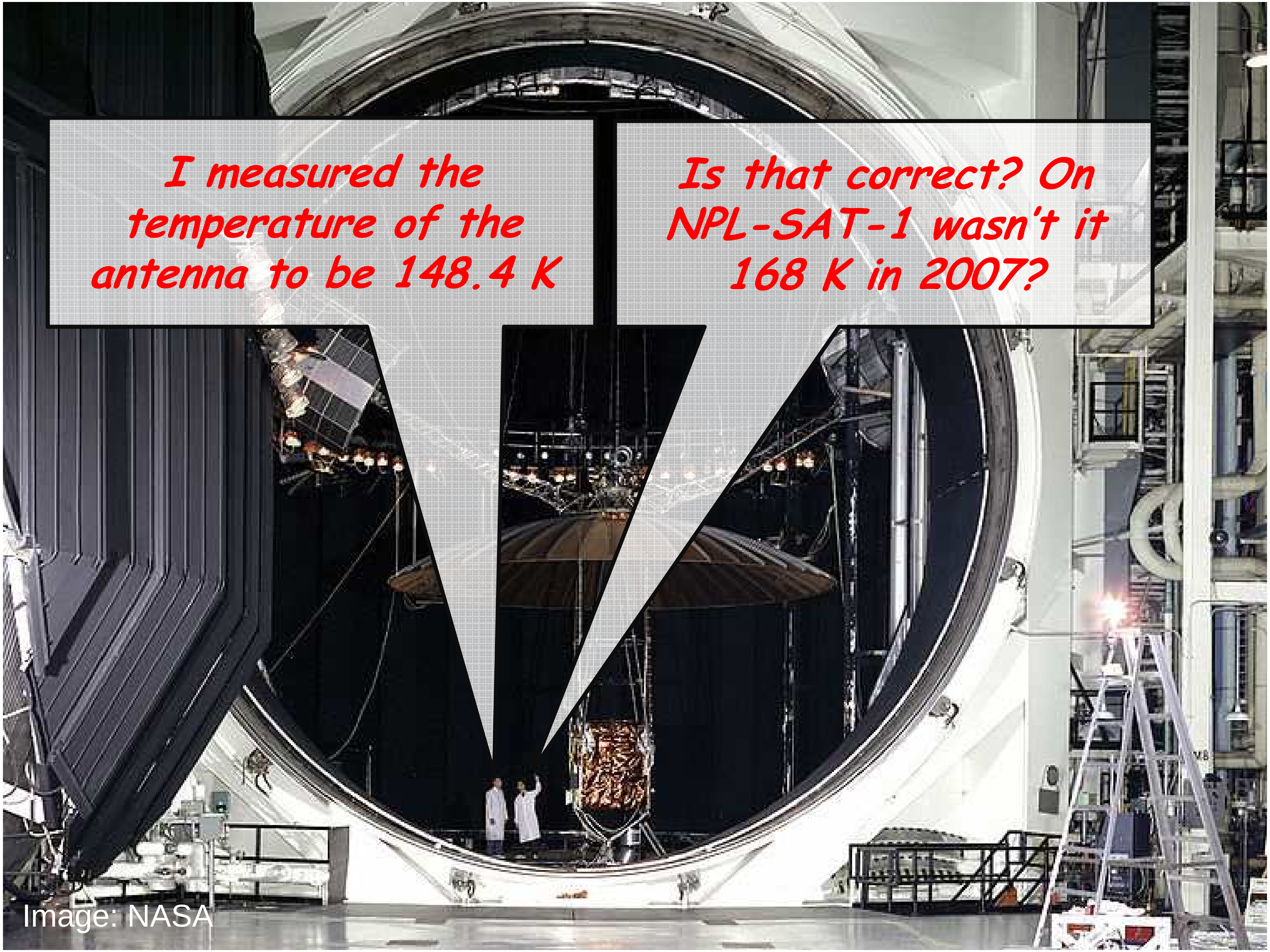
How will you know what the temperature is next year?

1. What’s the point?

2. The new SI

3. The new kelvin

4. What was the point again?


I measured the temperature of the antenna to be 148.4 K
Is that correct? On NPL-SAT-1 wasn't it 168 K in 2007?
Image: NASA

Temperature Measurement Matters

We need the temperature measurement system to be:

- **Stable**
  - Enables comparability over time
- **Consistent**
  - Enables comparability over distance and across boundaries

Additionally the system should:

- **Not be too complicated or expensive**
  - So that people actually use it
- **Provide measurement uncertainty required**
  - Subject to the historical trend to always make things better!
- **Be reasonably close to thermodynamic temperature**

The SI kelvin disseminated through the ITS-90 provides all this already!

So why are we re-defining the kelvin?

- **The International System of Units (the SI) is built on the MKSA system**
- **MKSA = metre-kilogram-second-ampere**
  - What’s the difference?
  - The SI has ‘People who care’

- **The SI is astonishingly successful**
  - But all complex structures need maintenance of their foundations
  - After all the work
    - Not much to ‘show’: except confidence in the structure

The kelvin re-definition is not about solving a problem we have today.

It is about building a system of measurement for an unknown future

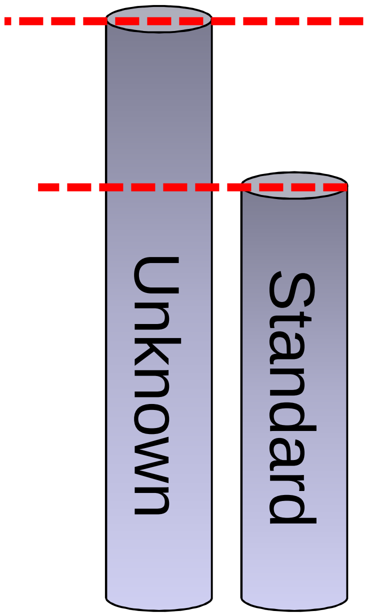
How will you know what the temperature is next year?

1. What’s the point?
2. The new SI
3. The new kelvin
4. What was the point again?

Measurement is…

Quantitative

Comparison…

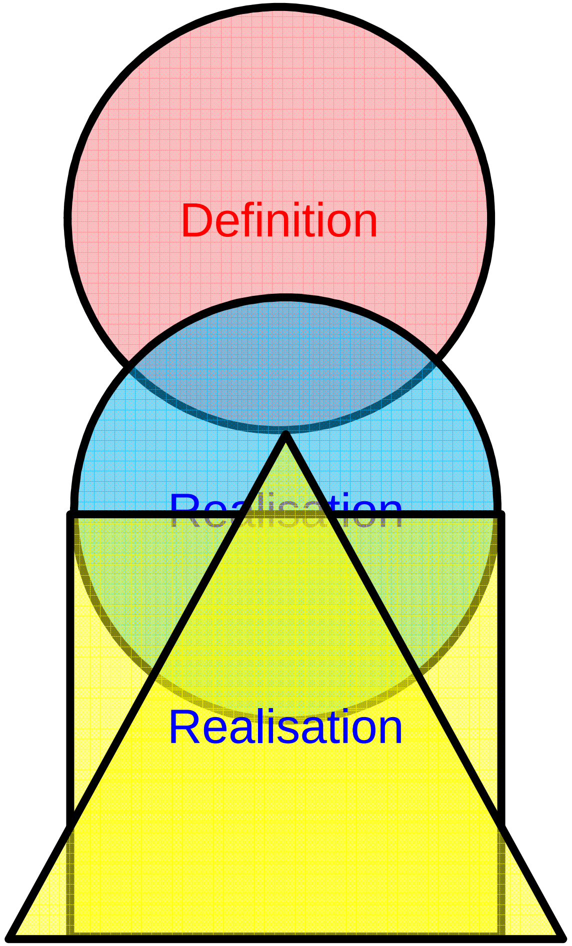


…of an unknown quantity with a standard quantity

Historically the definition of a standard was also its realisation.

Definitions and Realisations

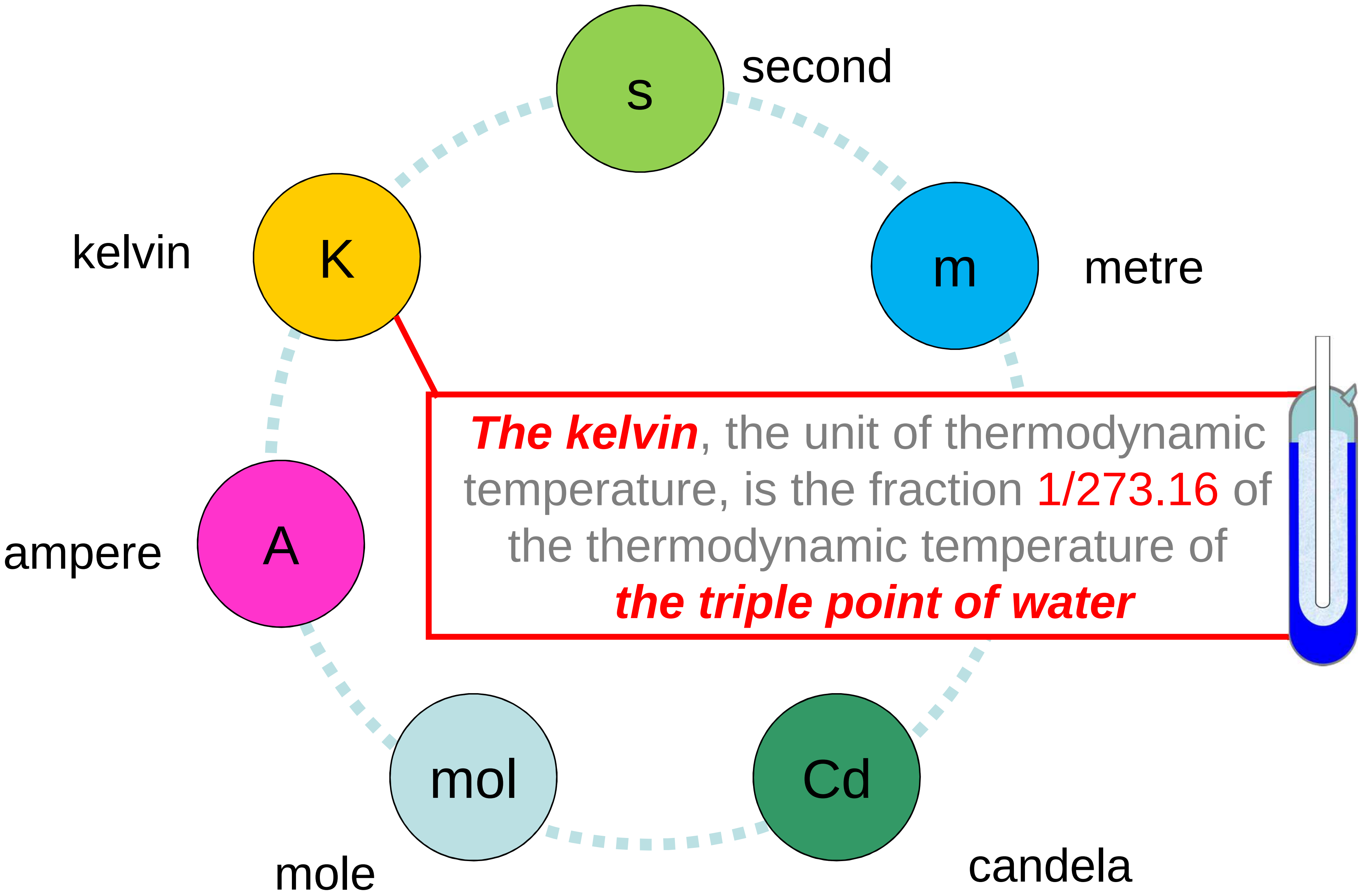
Traditionally unit definitions include some part of their preferred mode of realisation



If we separate the definition from the realisation…

…we allow realisations to evolve over decades and centuries in ways we cannot anticipate

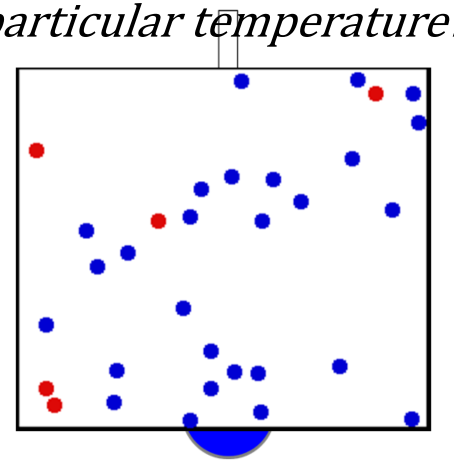
The International System of Units

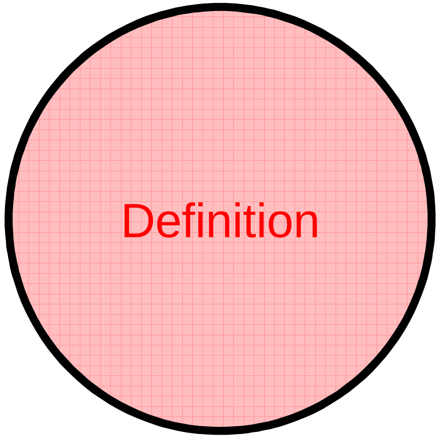


Definitions and Realisations

How many joules of energy do molecules possess at a particular temperature?

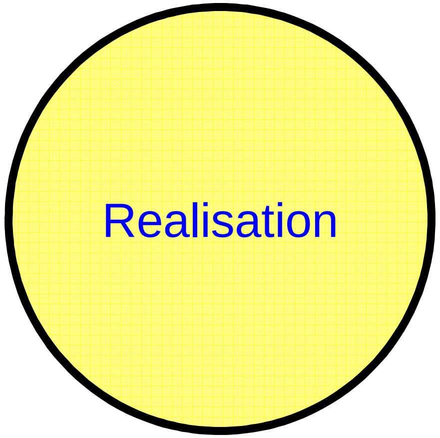
k_B





The definition

What we mean by 'one kelvin'



Realisation

How we translate that meaning into practical standards

Definitions and Realisations

How many joules of energy do molecules possess at a particular temperature?

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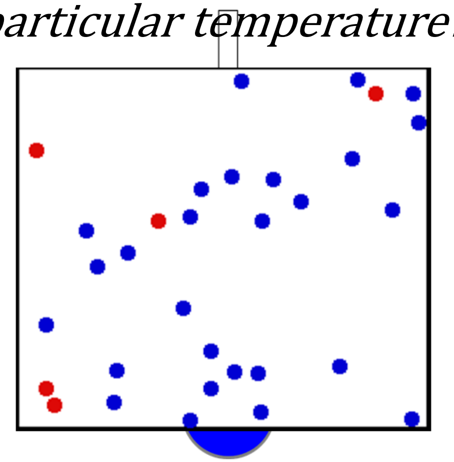

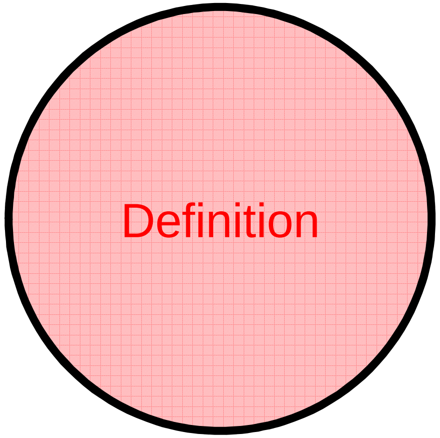

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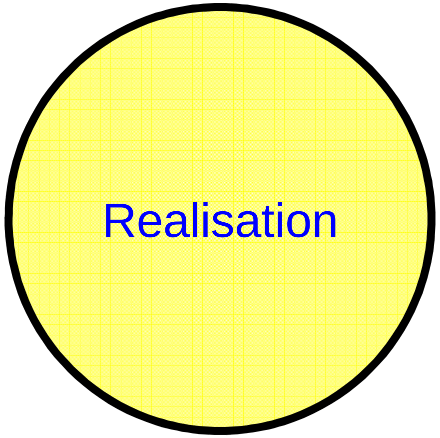


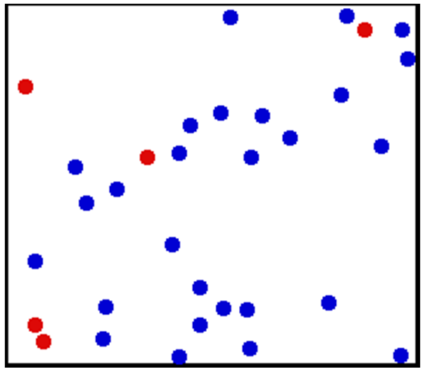
Realisation

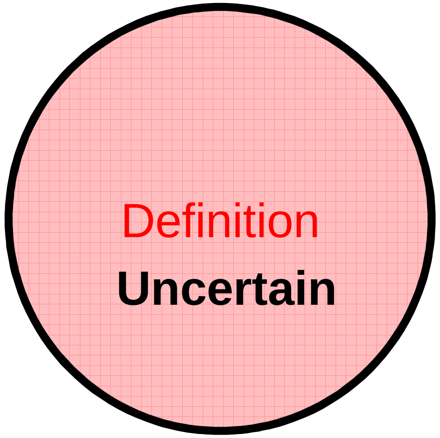
How we translate that meaning into practical standards

Definitions and Realisations **and Uncertainty**

How many joules of energy do molecules posses at a particular temperature

k_B





The definition

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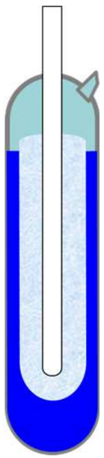
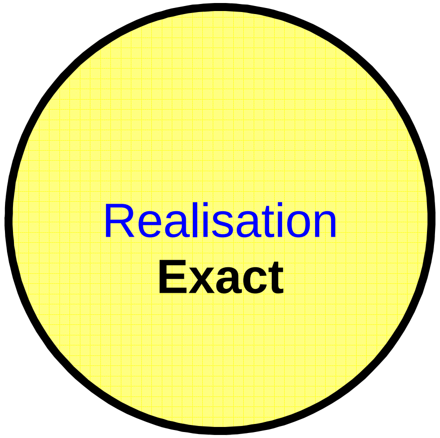


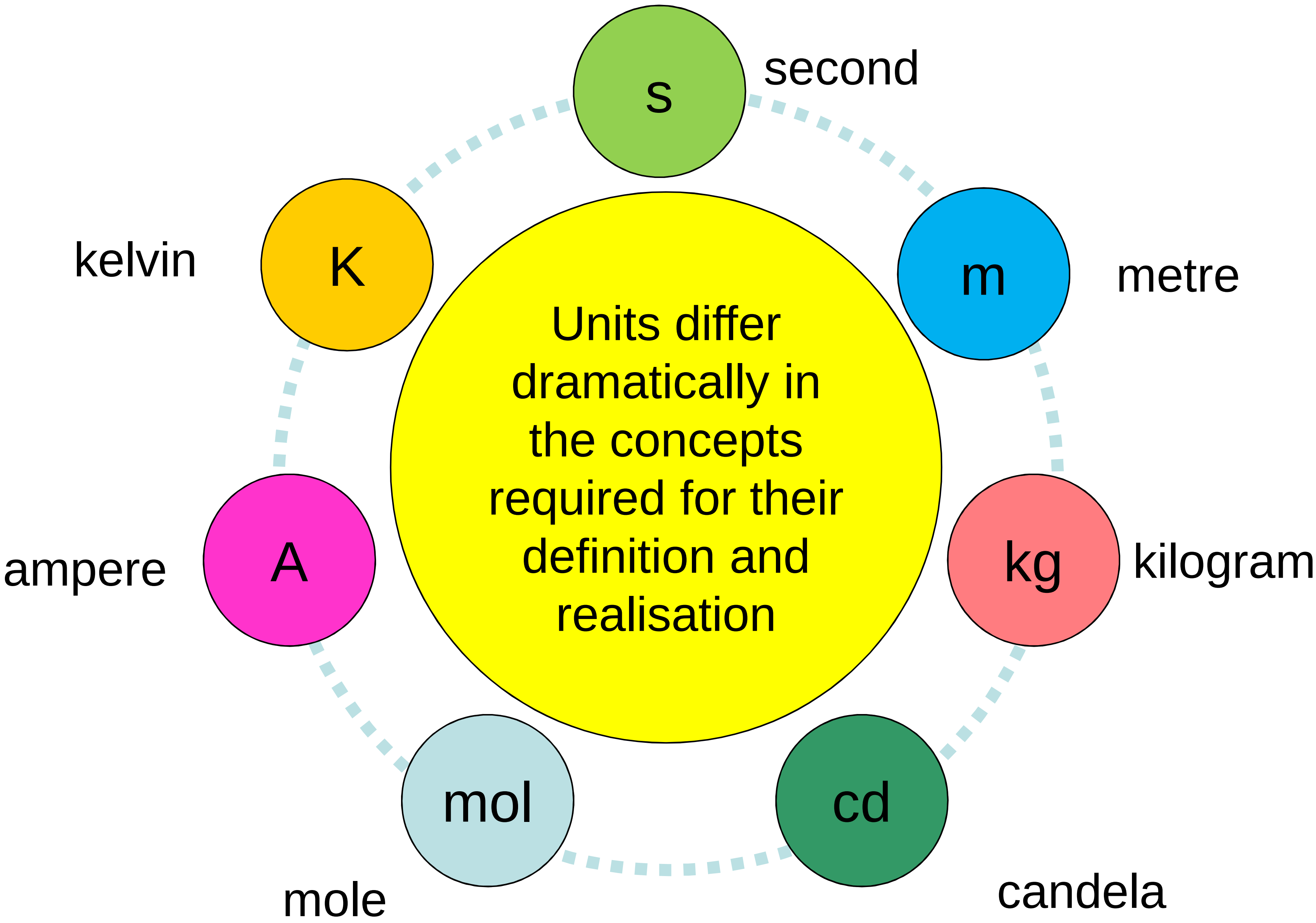


Realisation

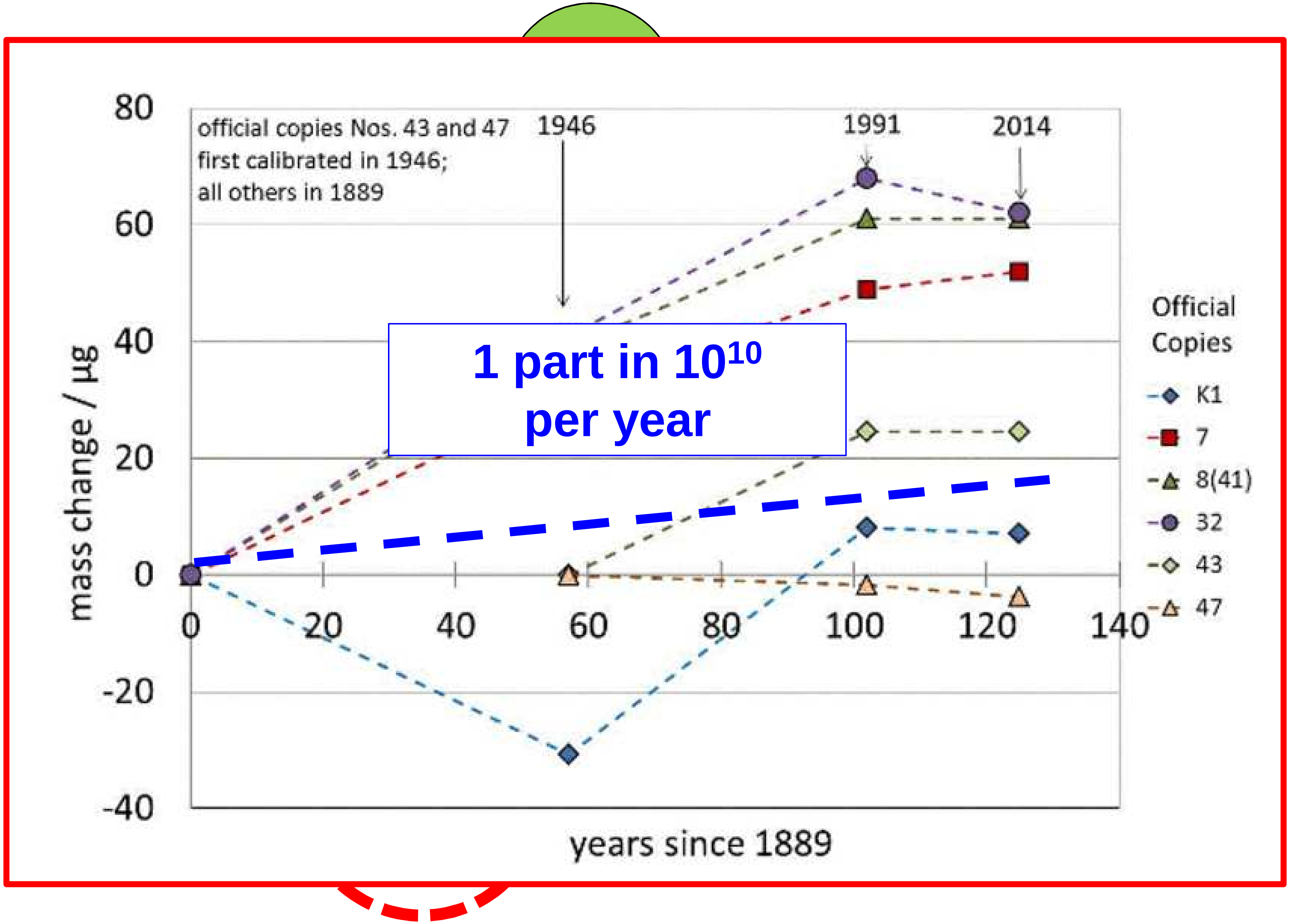
How we translate that meaning into practical standards

The International System of Units

The Current International System of Units



The Current International System of Units

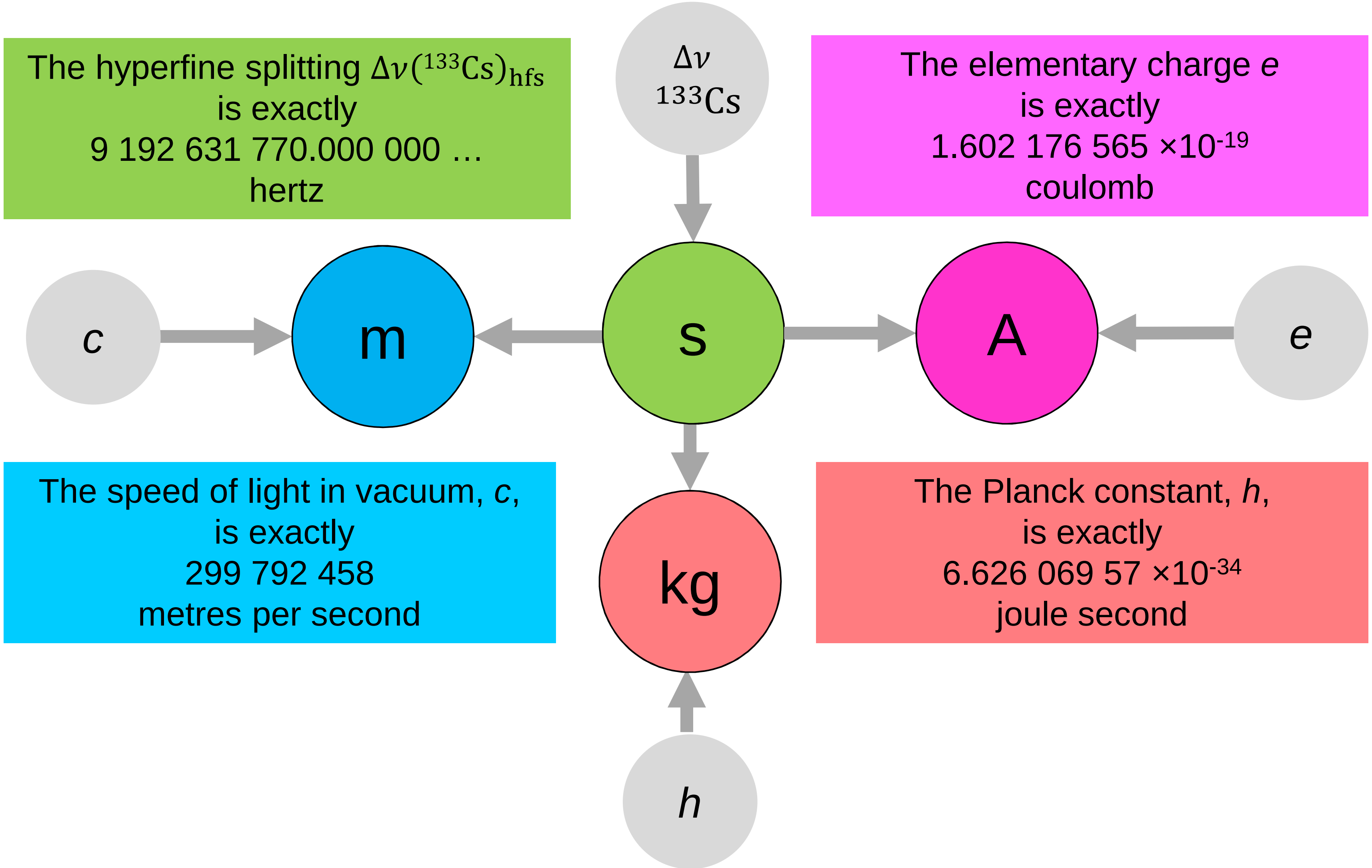


Unit Status…

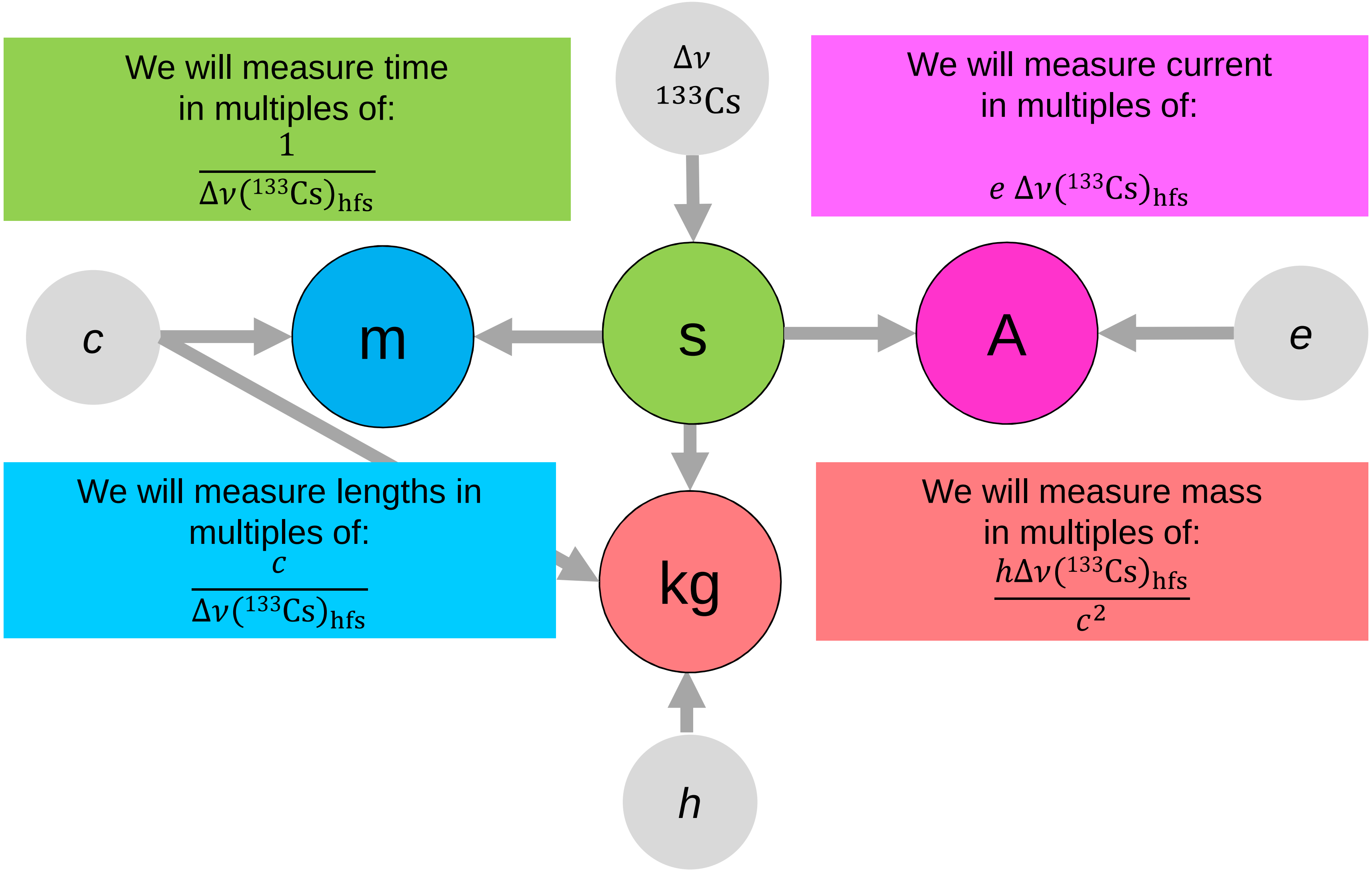
Unit	**Problems with the definition?**
Second	Successful: May need updating for new atomic transition
Metre	Successful
Kilogram	*Unsatisfactory. The International Prototype is drifting!*
Ampere	*Unsatisfactory. Since 1990 realisations of the ampere (and volt and ohm) are using the new SI definitions!*
Candela	Adequate
Mole	Successful: But definition linked to mode of realisation
Kelvin	Successful: But definition linked to mode of realisation No link to the unit definitions for energy

The ‘Core’ Units

The NEW International System of Units…
…is the system of units in which…



So in future…



We will measure time in multiples of: $\frac{1}{\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}}$
$\Delta\nu$ $^{133}\mathrm{Cs}$
We will measure current in multiples of: $e\,\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$
c
m
s
A
e
We will measure lengths in multiples of: $\frac{c}{\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}}$
kg
We will measure mass in multiples of: $\frac{h\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}}{c^2}$
h

The core of the 'New SI'…

- Based on our belief that *c*, *h* and *e* have not changed for a long time

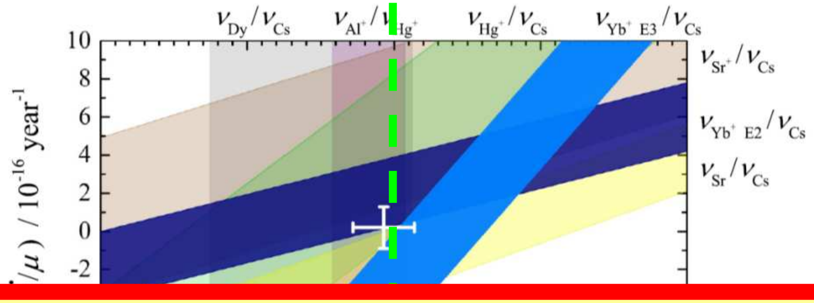
$$\alpha = \frac{e^2}{hc}$$

- The stability of the α can be measured using atomic clocks

Improved Limit on a Temporal Variation of mp/me from Comparisons of Yb+ and Cs Atomic Clocks
N. Huntemann, B. Lipphardt, Chr. Tamm, V. Gerginov, S. Weyers, and E. Peik
Physical Review Letters ***113****, 210802 2014* – Published November 17, 2014

Frequency Ratio of Two Optical Clock Transitions in Yb+171 and Constraints on the Time Variation of Fundamental Constants
R. M. Godun, P. B. R. Nisbet-Jones, J. M. Jones, S. A. King, L. A. M. Johnson, H. S. Margolis, K. Szymaniec, S. N. Lea, K. Bongs, and P. Gill
Physical Review Letters ***113****, 210801 2014* – Published November 17, 2014

2014 Experimental tests of the stability of α



NPL

$-0.7 \pm 2.1 \times 10^{-17}$ per year

α is at least

<u>*one million times*</u>

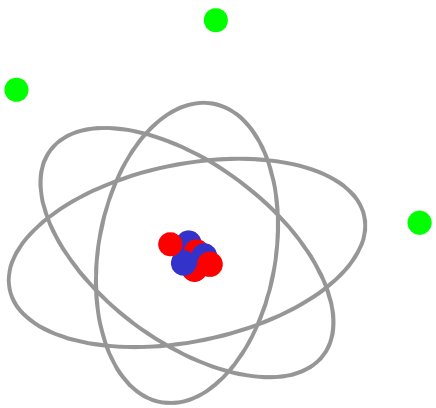
more stable than the

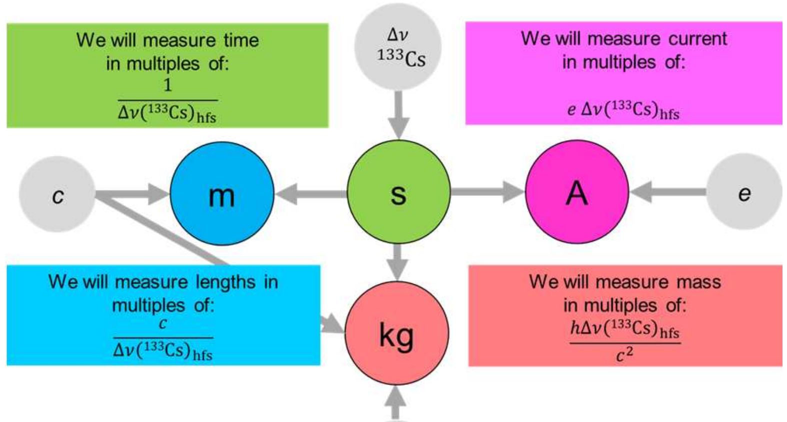
international prototype of the kilogram

$-2.0 \pm 2.0 \times 10^{-17}$ per year

$$\frac{1}{\alpha}\frac{d\alpha}{dt}\ (10^{-16}\ per\ year)$$

Uncertainty





Previously:

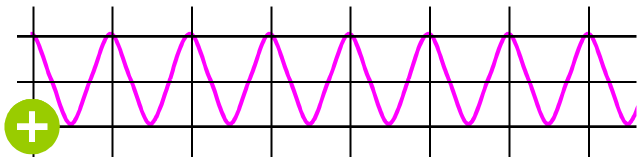
- We scaled our measurement system to human-scale artefacts
- ‘Constants’ needed to be measured and so had measurement uncertainty

In this conception of the SI

- We scale our measurement system to ‘natural constants’
- The constants in the unit *definitions* have no uncertainty.

This is not magic or trickery!

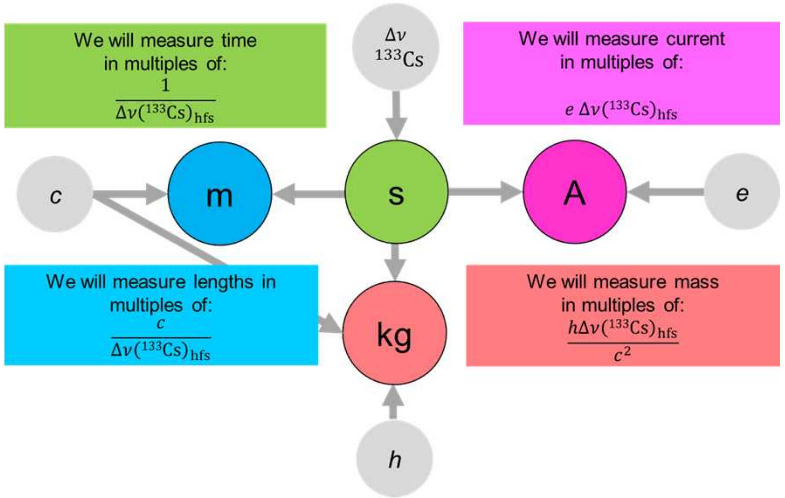
- It simply places the measurement uncertainty in a part of the traceability chain where it can be reduced without requiring a unit re-definition.



Abstraction

The new definitions are more abstract.
Improves the longevity of the definitions

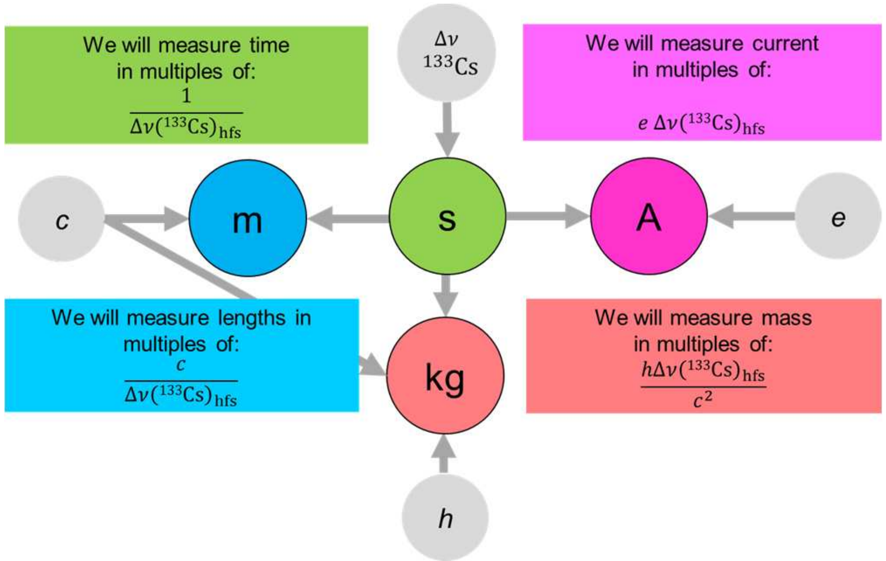
How do we explain how fixing h defines a unit of mass?



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 x 10^{-7} newton per metre of length.

How do we explain how this defines a unit of electric current?

Summary

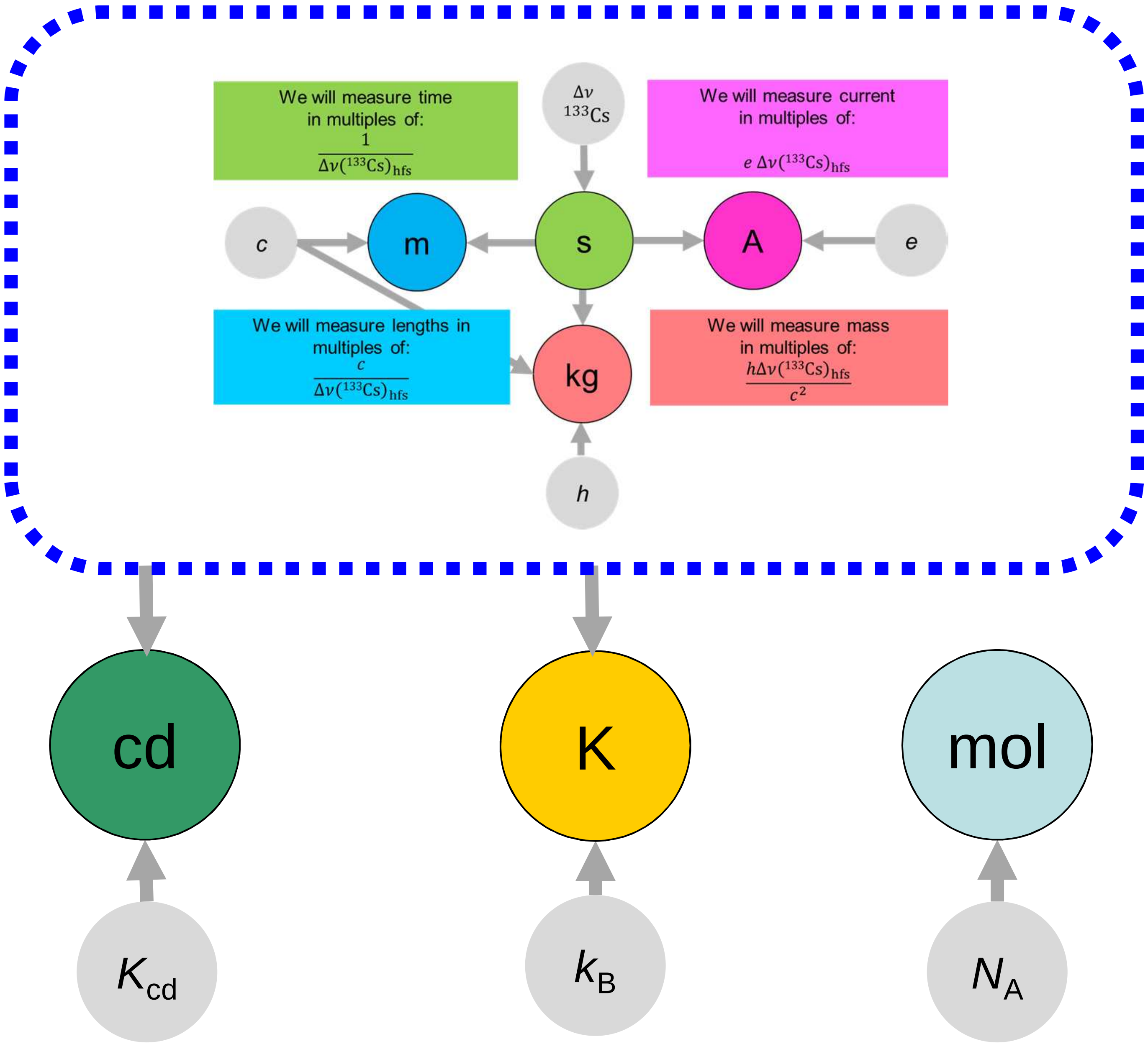


The definitions of ‘core units’ in the new SI are extremely satisfactory:

- They simply specify ‘natural constants’
- Their abstraction leads to the possibility of improvement in the technology of realising the units without affecting the definition.
- The long-standing ‘Ampere problem’ is resolved
- The ‘Kilogram problem’ is resolved. Just.

The ‘Non-Core’ Units

There are three non-core units in the new SI…



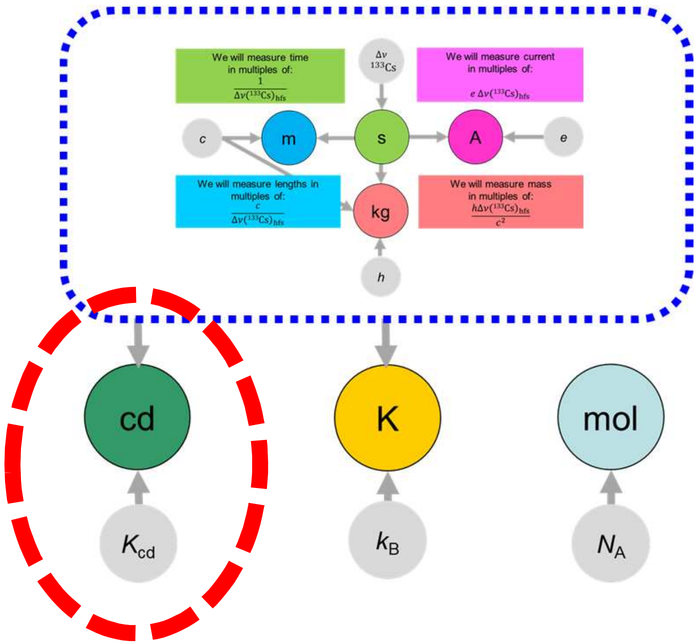
The ‘new’ candela…

Key concept is unchanged.

K_{cd} is simply re-stated as an ‘explicit constant’

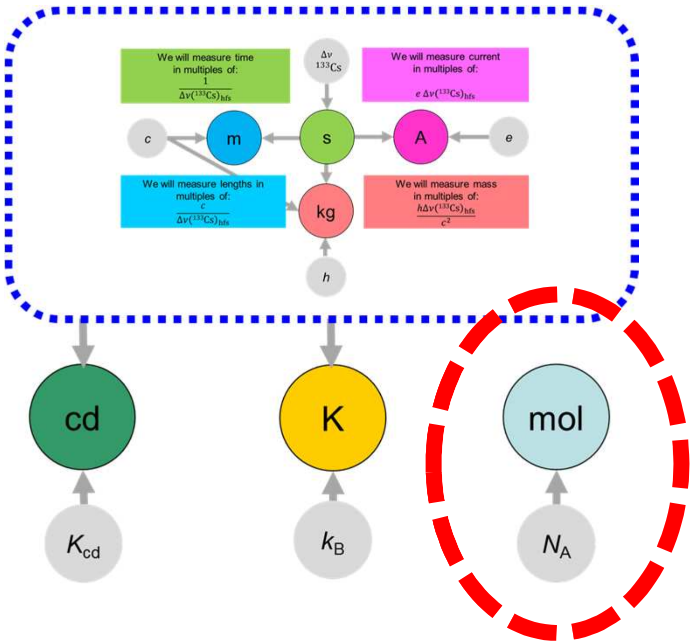
The luminous efficacy, K_{cd}, for monochromatic radiation of frequency 540 $\times 10^{12}$ Hz is exactly 683 when it is expressed in the SI units cd·sr/W = lm/W

The unique feature of the candela is that it is linked to human perceptions which are likely to vary from person to person.



The ‘new’ mole…

Redefinition is a consequence of the kilogram re-definition.



Previously:

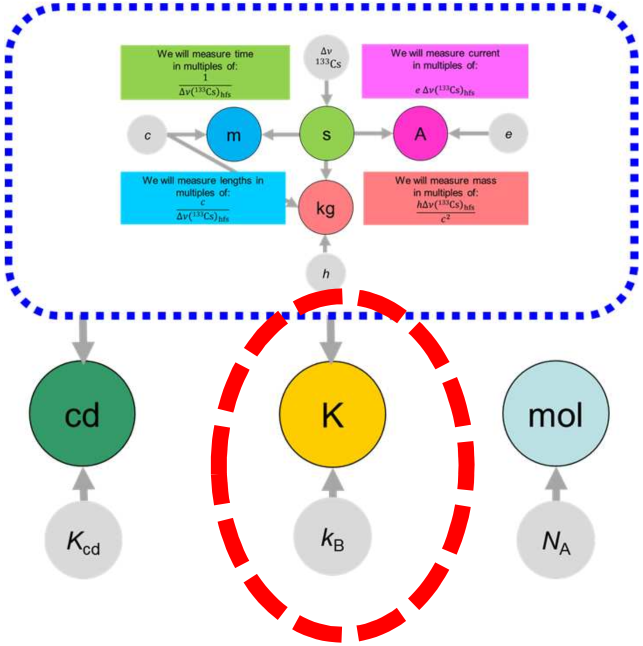
- **The number of atoms in 12 g of ^{12}C**

Proposed:

- ***N_A* elementary entities where *N_A* = 6.022 141 29 $\times 10^{23}$ *exactly***
- Recognises that Chemistry is about *stoichiometry*, not mass
- What was previously a definition of the mole – a weighing procedure – now becomes a technique for realising the mole.

The kelvin…

Redefinition links kelvin to the concept of molecular energy



Previously:

- T_{TPW} **= 273.16 K *exactly***

Proposed:

- k_B **= 1.380 648 52×10^{-23} joules per kelvin *exactly***
- $N_A \times k_B = R$ **= 8.314 459 86 joules per kelvin per mole *exactly***

  - Recognises the statistical mechanical nature of temperature
  - Temperature measurements no longer tied to T_{TPW}

The ‘New’ SI

- **Builds the SI on the most stable things we know:**
  - Natural Constants
- **Removes uncertainty from *definitions* of the units:**
  - There will always be uncertainties in how units are realised.
- **Corrects problems with:**
  - Kilogram
  - Ampere
- **Consequences for:**
  - mole

Why are we re-defining the kelvin?

How will you know what the temperature is next year?

1. What’s the point?
2. The new SI
3. The new kelvin
4. What was the point again?

The definition of the kelvin in the new SI

Rationale

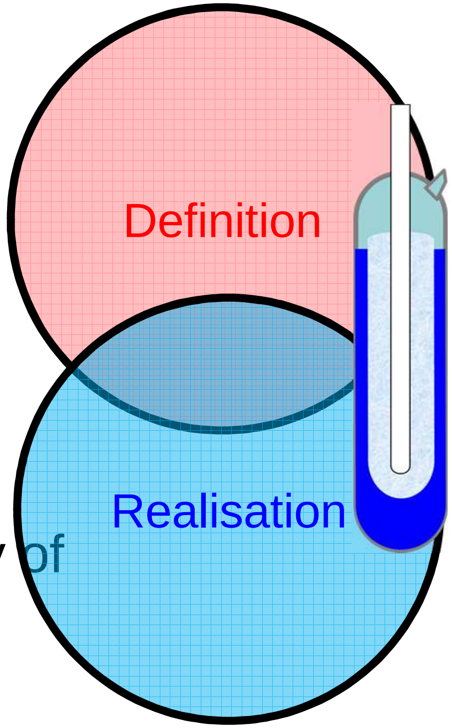
Implementation

Implications

What was the alternative?

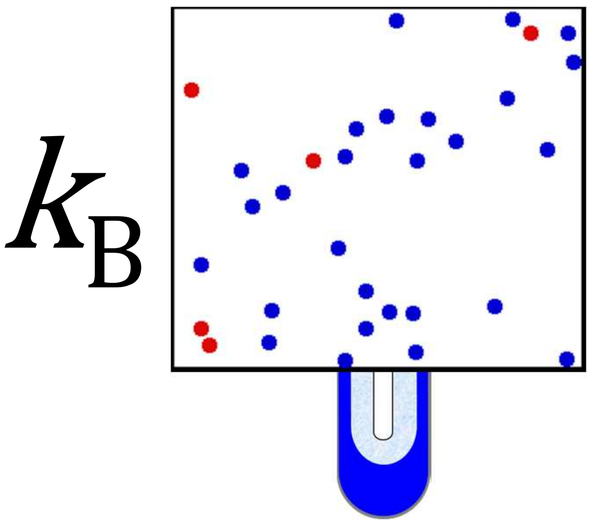
To define the kelvin in the same style as the rest of the new SI

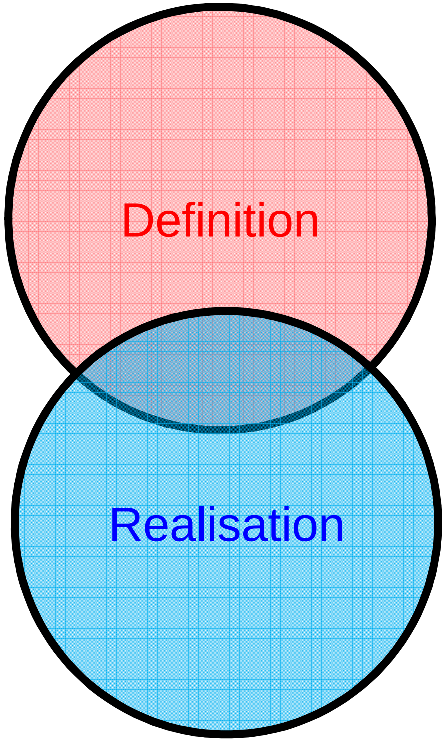
- **We *could* have used the explicit constant definition to re-state**
  - "T_{TPW} = 273.16 K exactly"
- **If we had chosen that:**
  - Then nothing would change.
  - No separation between definition and realisation.
  - In the context of the new SI, it implies T_{TPW} is fundamental to what we *mean* by temperature
  - No possibility of ever improving beyond realise-ability of T_{TPW}
    - Inhibits possible technological or theoretical progress, especially at temperature extremes.
  - No connection to the rest of the SI and the concept of Energy



The choice to base the kelvin on a defined value of k_B is profound:

- It creates a ‘modern’ unit definition.
- It acknowledges underlying molecular reality.





Why has this taken so long?

Thermal pioneers

- **Anders Celsius (1710) and Daniel Gabriel Fahrenheit (1724)**
  - *Allowed people to investigate the world*
  - *Thermometers were useful*

- **Jean-Baptiste Joseph Fourier (1807 - 1820)**

No consensus on what thermometers measured!

  - *Theory of Free and Perfectly Elastic Molecules in a State of Motion*

- **James Clerk Maxwell (1859-1866)**
- **Ludwig Boltzmann (1866)**
- **Josiah Willard Gibbs(1901)**
  - *The kinetic theory of gases*

- **John Tyndall (1865)**
  - Wrote the textbook: “Heat: a mode of motion”

- **John Baptiste Perrin (1926)**
  - Nobel prize for finally demonstrating the existence of atoms

Jean Baptiste Joseph Fourier

Analytical Theory of Heat

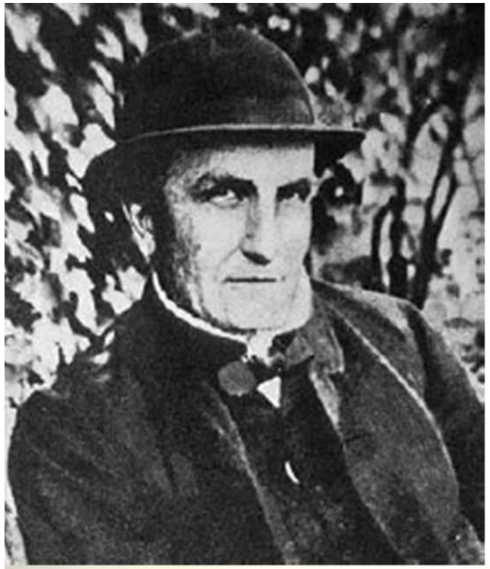
PRIMARY causes are unknown to us; but are subject to simple and constant

Newton comprised the system of the universe. It is recognised that the same principles regulate all the movements of the stars, their form, the inequalities of their courses, the equilibrium and oscillations of the seas, the harmonic vibrations of the air and sonorous bodies, the transmission of light, capillary actions, the undulations of fluids

But whatever may be the range of mechanical theories, they do not apply to the effects of heat. These make up a special order of phenomena which cannot be explained by the principles of motion and equilibrium.

But whatever may be the range of mechanical theories, they do not apply to the effects of heat. These make up a special order of phenomena, which cannot be explained by the principles of motion and equilibrium. We have for a long time been in possession of ingenious instruments adapted to measure many of these effects; valuable observations have been collected; but in this manner partial results only have become known, and not the mathematical demonstration of the laws which include them all.

Preliminary Discourse



John James Waterston (1845)

On the Physics of Media that are Composed of Free and Perfectly Elastic Molecules in a State of Motion

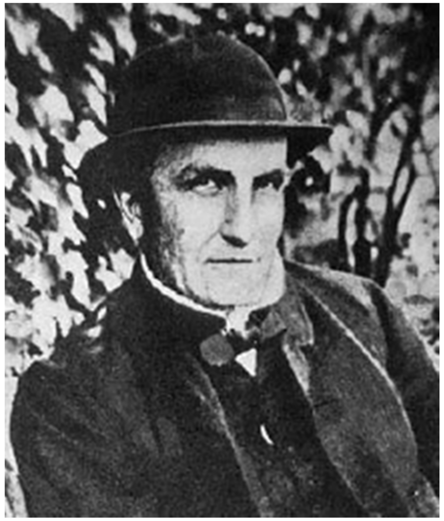
PHILOSOPHICAL TRANSACTIONS.

I. *On the Physics of Media that are Composed of Free and Perfectly Elastic Molecules in a State of Motion.*

By J. J. WATERSTON.

Communicated by Captain BEAUFORT, *R.N., F.R.S., &c.*

Received December 11, 1845,—Read March 5, 1846.



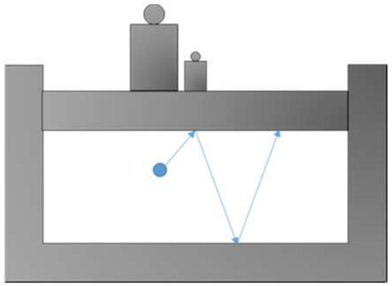
To have a proper conception of what the medium is that forms the subject of

…we must imagine a vast multitude of small particles of matter, perfectly alike in every respect

…the condition of the multitude … that form the medium may be likened to the familiar appearance of a swarm of gnats in a sunbeam.

medium may be likened to the familiar appearance of a swarm of gnats in a sunbeam.

…The quality of perfect elasticity being common to all the particles, the original amount of *vis viva* …of the whole multitude must forever remain the same… as unchanged as the matter that is associated with it.



The medium must in this way become endowed with a permanent state of elastic energy, or disposition to expand, uniformly sustained in every part and communicating to it the physical character of an elastic fluid.

Pages 6 & 7

JJ Waterston's Predictions

Waterston shows that a medium of this kind:

- Would obey the laws of Mariott, Dalton and Gay-Lussac
- The *Vis Viva* (Kinetic Energy) would be 'like Temperature' i.e. $k_B = 1$
- *Vis Viva* would equally distributed, even amongst molecules of differing

"The paper is nothing but nonsense"

Referee 1845

- Calculates the 'mechanical equivalent of heat' (measured by Joule)
- States that the 'Absolute Zero' of temperature (~-480 °F) is when the *vis viva* of molecules is zero

"***The omission to publish it at the time was a misfortune which probably retarded the subject by 10 to 15 years."***

Commentary by Lord Rayleigh in 1896

John Tyndall

HEAT: a Mode of Motion 1865

HEAT

CONSIDERED AS

A M

1865.

The right of translation is reserved.

PREFACE

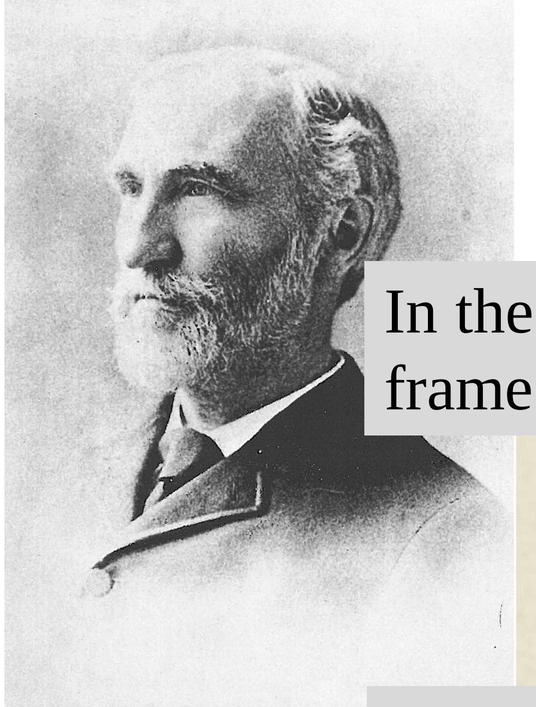
In the following Lectures I have endeavoured to bring the rudiments of a new philosophy within the reach of a person of ordinary intelligence and culture.

The first seven Lectures of the course deal with thermometric heat; its generation and consumption in mechanical processes; the determination of the mechanical equivalent of heat; the conception of heat as molecular motion; the application of this conception to solid, liquid and gaseous forms of matter; to expansion and combustion; to specific and latent heat and to calorific conduction..

the possible sources of his energy; the relation of this energy to terrestrial forces, and to vegetable and animal life.

My aim has been to rise to the level of these questions

Josiah Willard Gibbs

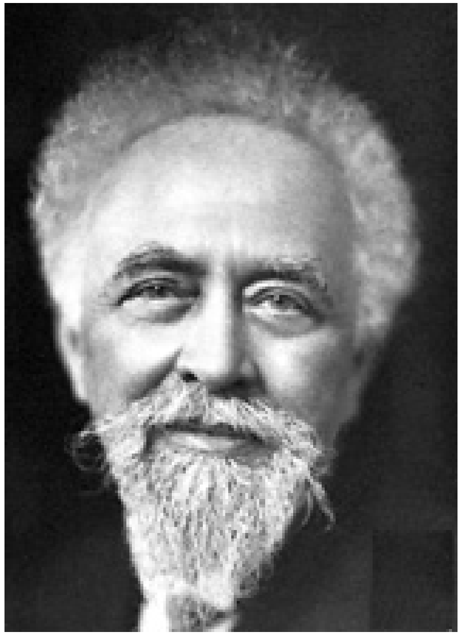


Elementary Principles in

In the present state of science, it hardly seems possible to frame a dynamic theory of molecular action…

the attempt to frame hypotheses concerning the constitution of material bodies, we pursue statistical inquiries as a branch of rational mechanics. In the present state of science, it seems hardly possible to frame a dynamic theory of molecular

Even if we confine our attention to the phenomena distinctively thermodynamic, we do not escape difficulties in as simple a matter as the number of degrees of freedom of a diatomic gas. It is well known that while theory would assign to the gas six degrees of freedom per molecule, in our experiments on specific heat we cannot account for more than five. ***Certainly, one is building on an insecure foundation who rests his work on hypotheses concerning the constitution of matter***.



Jean Baptiste Perrin

Nobel Prize for Physics 1926

"for his work on the discontinuous structure of matter, and especially for his discovery of sedimentation equilibrium".

BROWNIAN MOVEMENT AND MOLECULAR REALITY.

BY M. JEAN PERRIN

(Professeur de Chimie Physique, Faculté des Sciences, Université de Paris.)

TRANSLATED FROM THE

ANNALES DE CHIMIE ET DE PHYSIQUE, 8me SERIES, *September* 1909,

BY F. SODDY, M.A., F.R.S.

92

Equating these two expressions we have a relation

$$f[a, a', a'', \ldots.] \equiv g[b, b', b'', \ldots.],$$

where only evident realities enter, and which expresses a profound connection between two phenomena at first sight completely independent, such as the transmutation of radium and the Brownian movement. For example, if we compare the law of the distribution of the energy A of dark radiation as a function of the wave-length (No. **41**) and the law of rarefaction of a uniform emulsion as a function of gravity (No. **14**), we perceive that these two laws are not independent and that the one is connected to the other by the equation

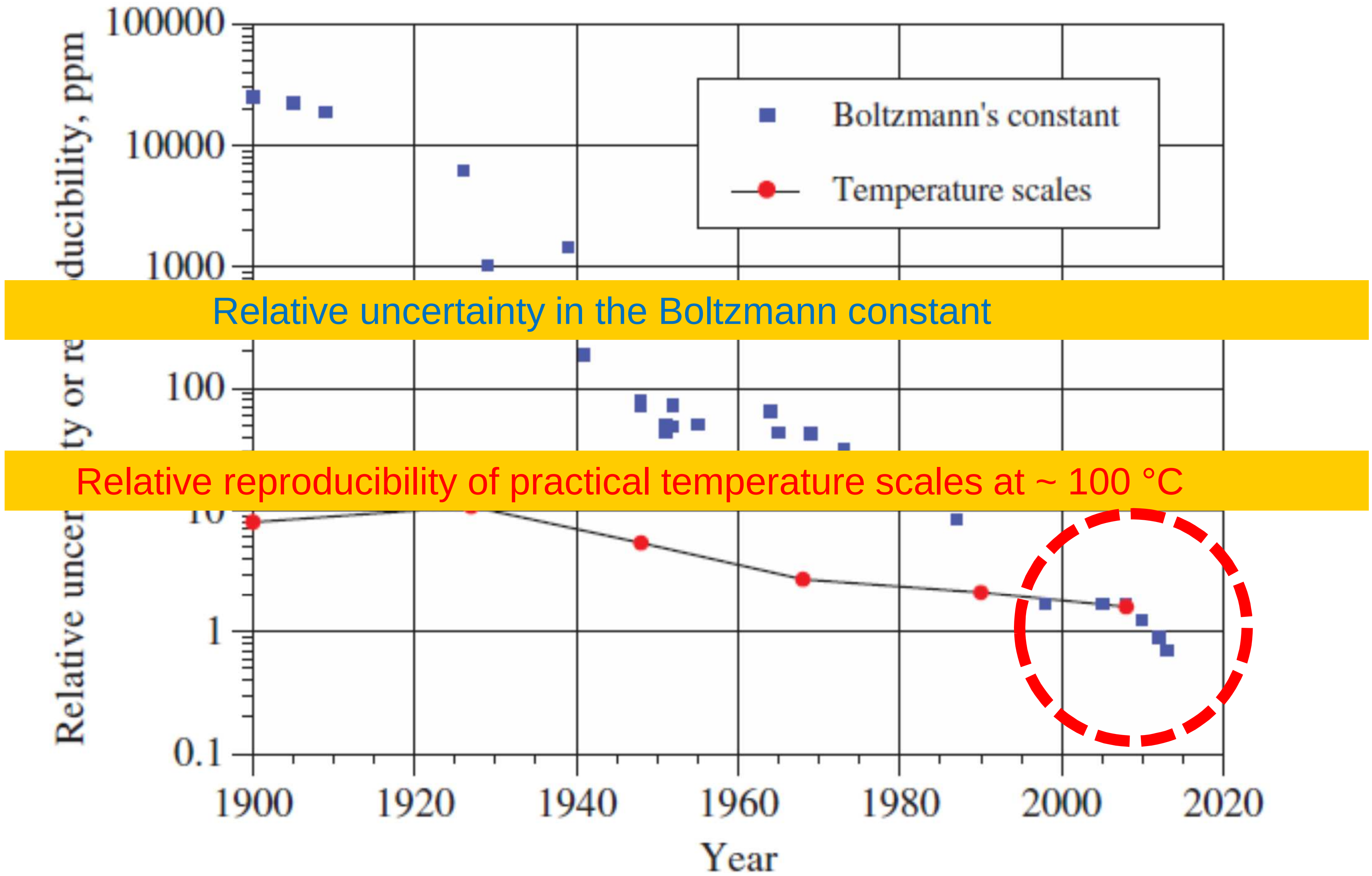
scientific consciousness.

The discovery of such relationships marks the point where the underlying reality of molecules becomes a part of our scientific consciousness.

Not only are our ideas clearer…

We have progressed experimentally…

We have (slowly) got better at measuring k_B



From *White and Fischer: Metrologia* **52** (2015) S213-S216

Why has this taken so long?

Historically…

- Temperature measurement became important for science and engineering before we understood what we were measuring!

- The need for reproducible measurements was more important than the link to statistical mechanics

Now…

- We accept the existence of atoms,
- We define the SI in terms of fundamental constants,
- We accept the validity of statistical mechanics
- We have (slowly) become better at measuring k_B

- ***But in metrological terms, there have been very few opportunities to revise our previous scepticism.***
- **(ITS-1927, ITS-1948, IPTS-1968, ITS-1990)**

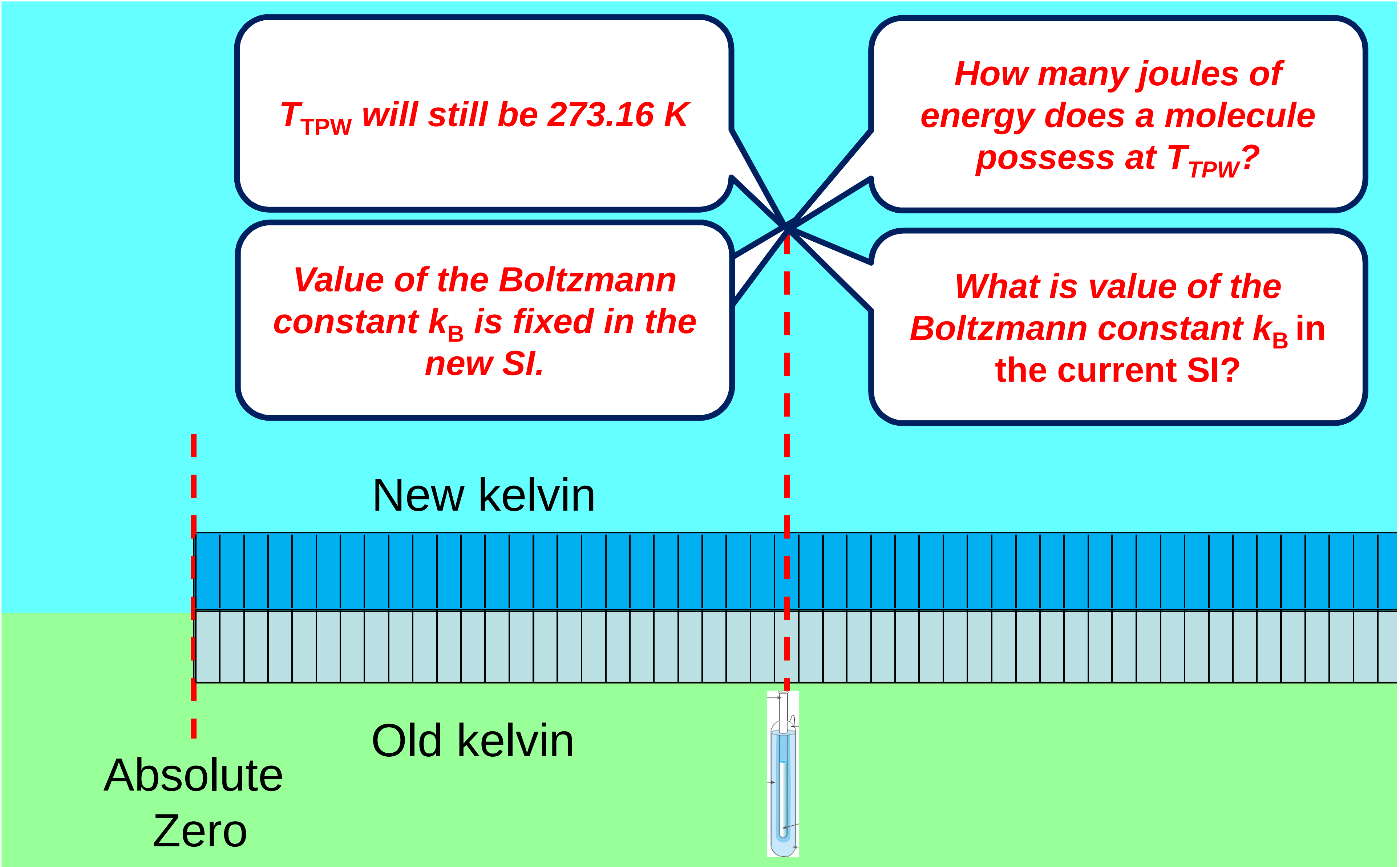
Rationale

Implementation

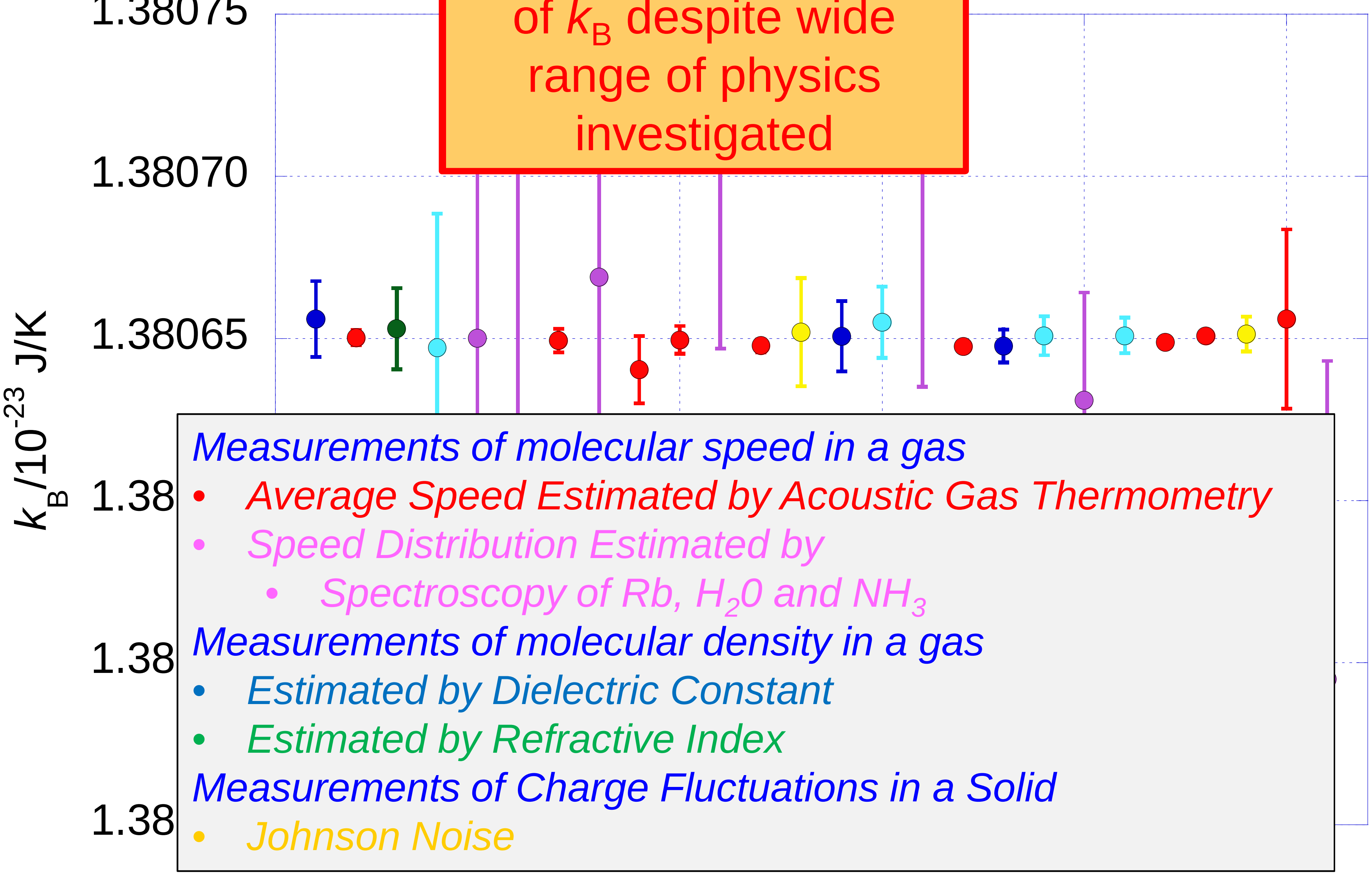
Implications

Changing from old to new

- We want the size of the kelvin to stay the same:



How do we know we have the right k_B?



Consistent estimates of k_B despite wide range of physics investigated

Measurements of molecular speed in a gas

- *Average Speed Estimated by Acoustic Gas Thermometry*
- *Speed Distribution Estimated by*
  - *Spectroscopy of Rb, H_20 and NH_3*

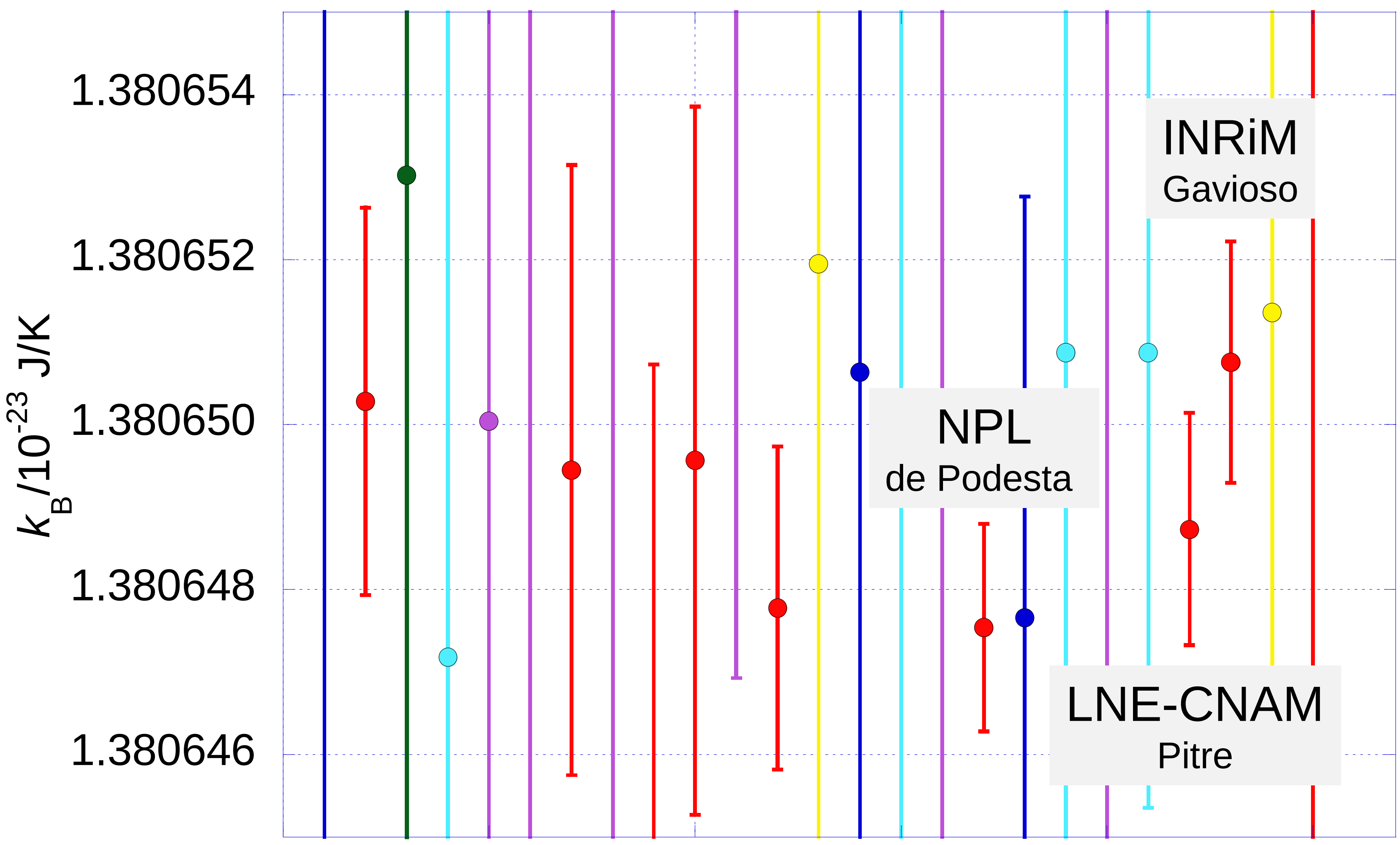
Measurements of molecular density in a gas

- *Estimated by Dielectric Constant*
- *Estimated by Refractive Index*

Measurements of Charge Fluctuations in a Solid

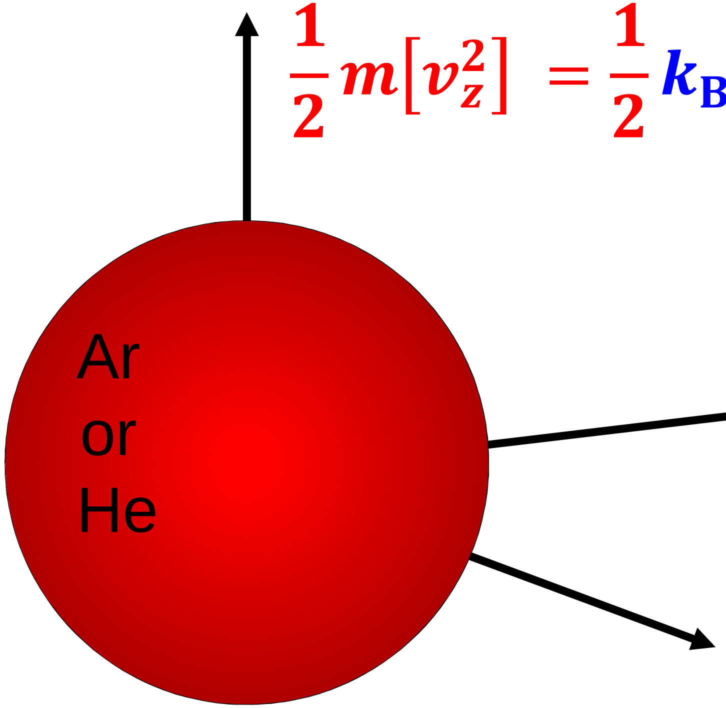
- *Johnson Noise*

How do we know we have the right k_B?



Molecular motion is simple in a gas

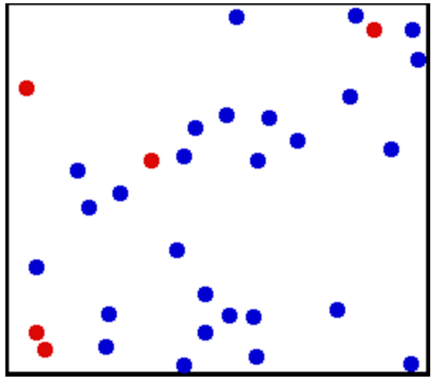
- We can approach ‘ideal gas’ conditions at low pressure
- In an ideal gas the internal energy is just the kinetic energy of the molecules



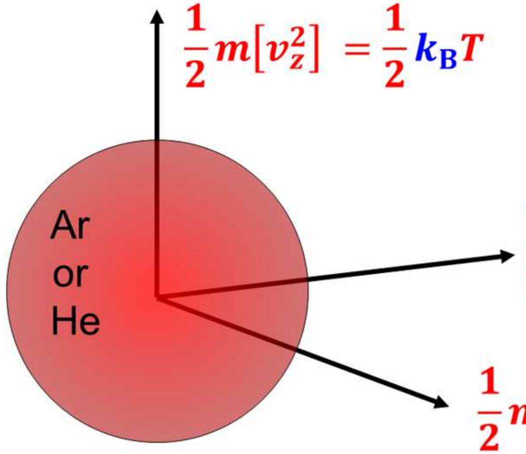
$$\frac{1}{2}m[v_z^2] = \frac{1}{2}k_B T$$

$$\frac{1}{2}m[v_y^2] = \frac{1}{2}k_B T$$

$$\frac{1}{2}m[v_x^2] = \frac{1}{2}k_B T$$



The big idea…



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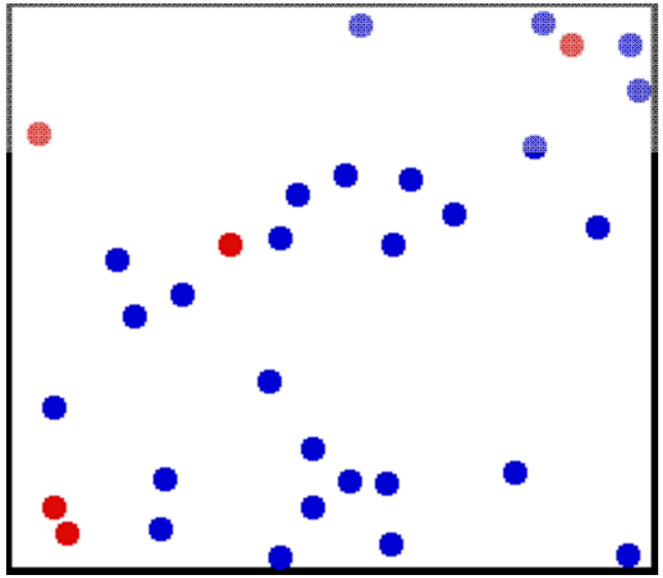


Look up mass of a molecule

$$k_B = \frac{3m}{5T}\,[\,speed\ of\ sound]^2$$

$$\frac{9}{5}(speed\ of\ sound)^2$$

Carry out experiment at T_{TPW}

Measure the speed of sound

CCT Task Group on the SI…

…requests CODATA to make its final adjustment of the value of the Boltzmann constant only when the following two conditions are met:

1. The relative standard uncertainty of the adjusted value of k_B is less than 1×10^{-6}

CODATA 2010 relative uncertainty equal to 9.1×10^{-7} .
CODATA 2014 relative uncertainty equal to 5.7×10^{-7} .

2. The determination of k_B is based on at least two fundamentally different methods, of which at least *one result for each* shall have a relative standard uncertainty less than 3×10^{-6} .

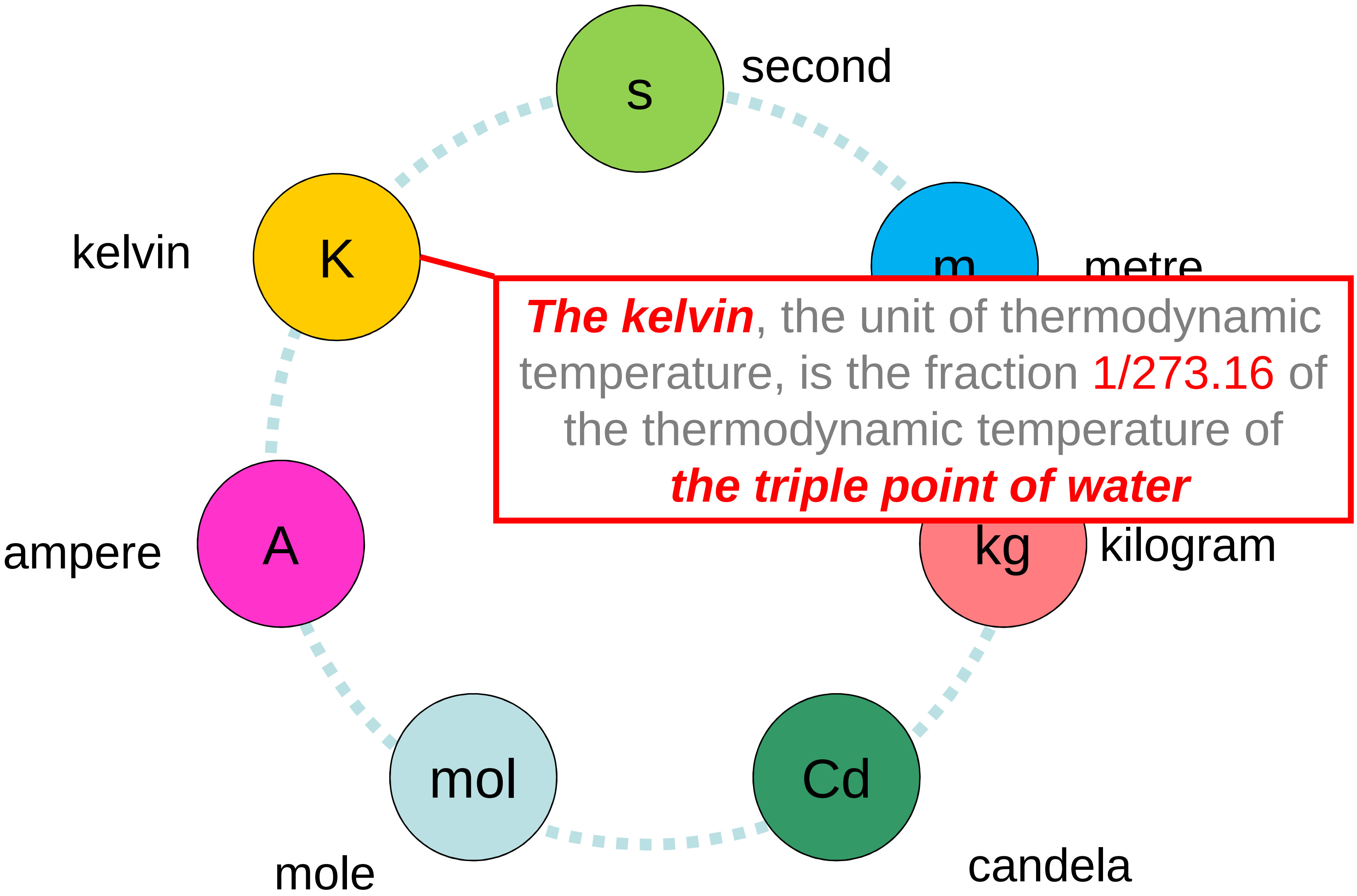
Not yet achieved.
But results expected before 2017

Rationale

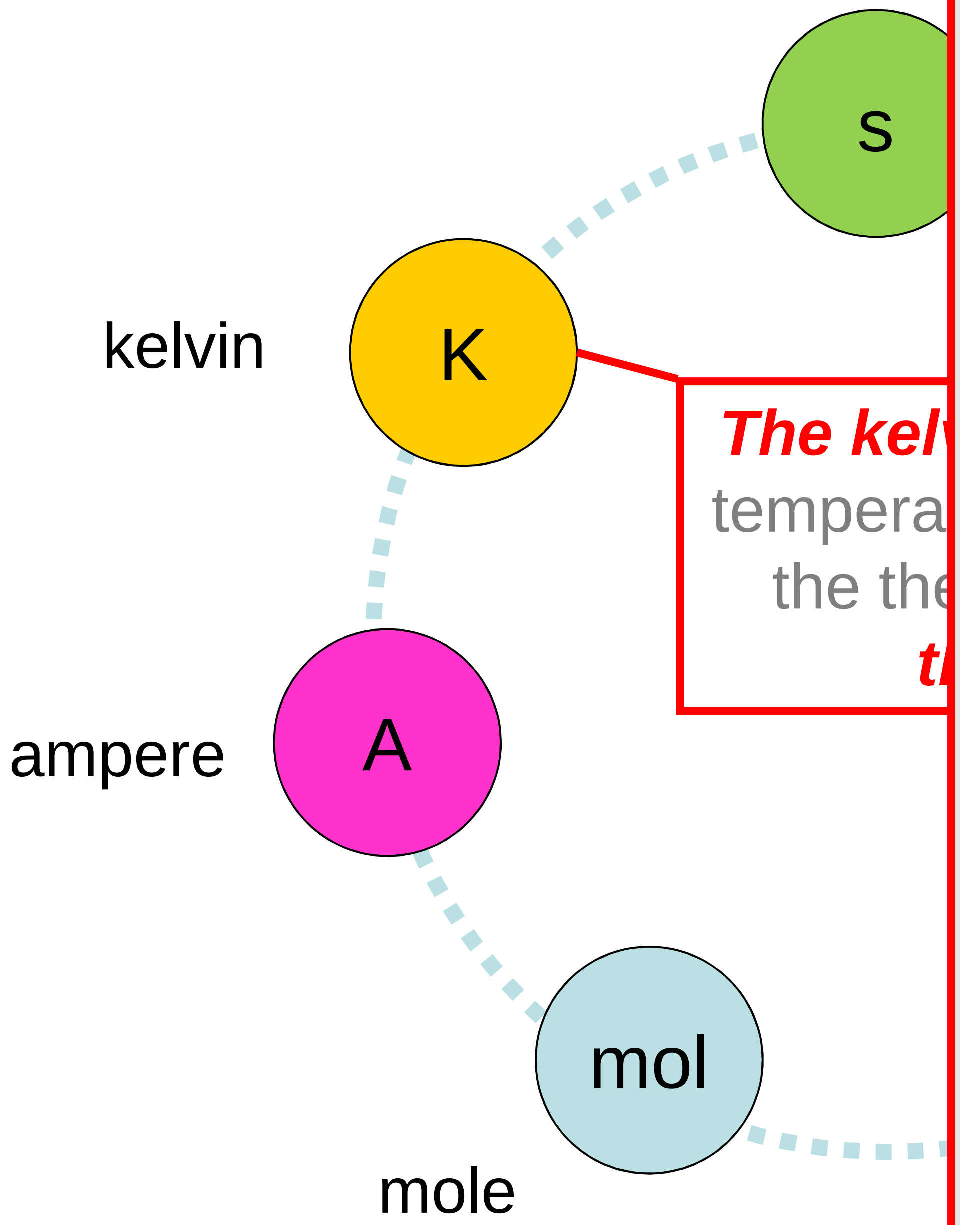
Implementation

Implications

The Old International System of Units



The Old International System of Units



Every **temperature measurement is a quantitative comparison of**

the 'level of molecular jiggling'

in the target with

the 'level of molecular jiggling'

in a triple-point cell

The International System of Units

kelvin

K

T_{TPW} **will still be a useful reproducible temperature**

But it will not *define* what we mean by 'one degree'

***Every* temperature measurement is a quantitative comparison of**

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The SI Joule (defined in terms of the product $h\Delta\nu$)

Triple point of water

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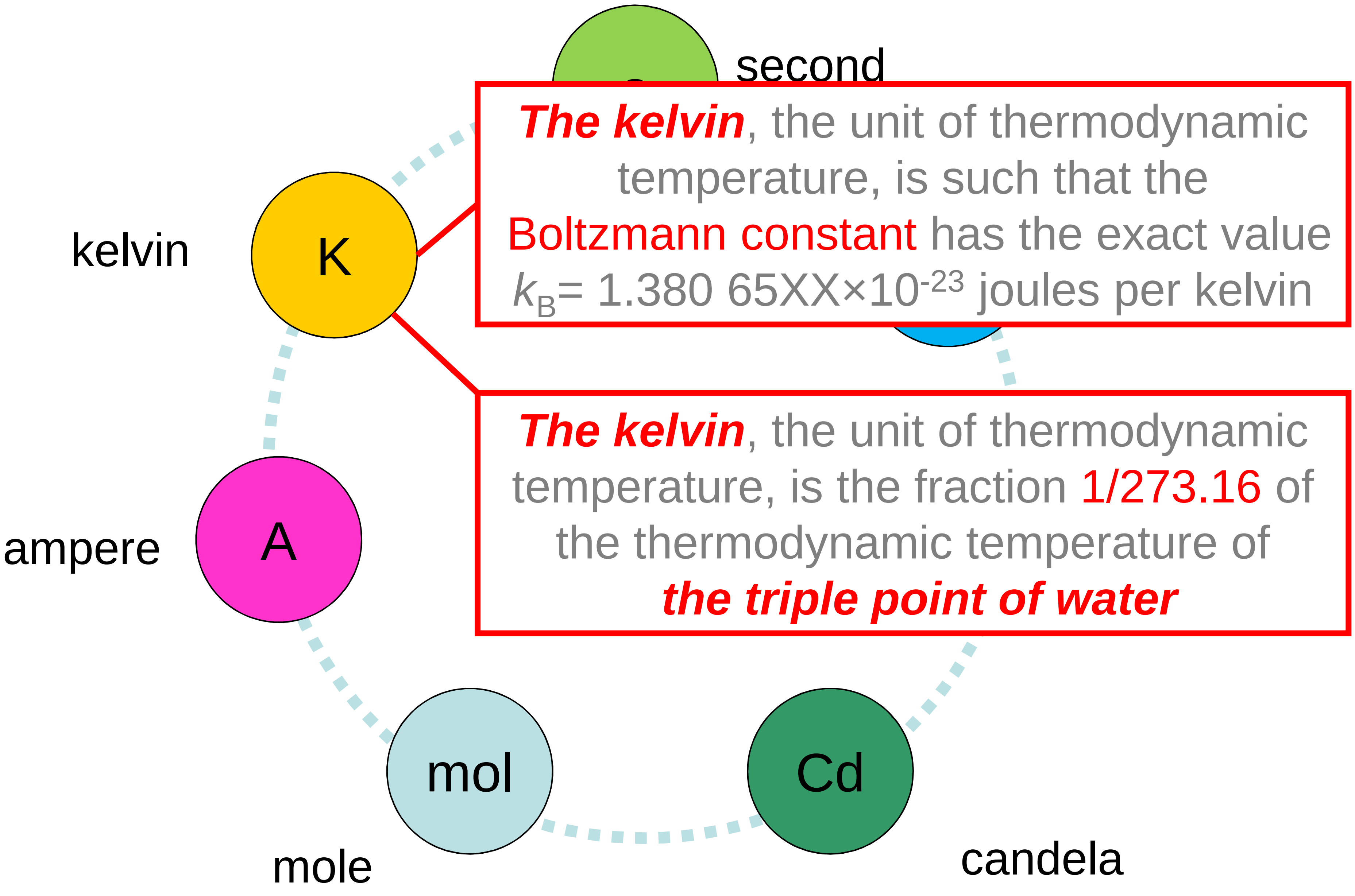
The International System of Units



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For temperature dissemination..

Immediately

- No consequences
- ITS-90 will still be based on the triple point of water
- The uncertainty in T_{TPW} (likely to be ~140 µK) will increase the thermodynamic uncertainty of all T_{90} estimates
  - But this is tiny compared to the known errors in T_{90}

- ***No impacts expected***

For Fundamental thermometry ‘close’ to T_{TPW}

Currently :

- We estimate T_{unknown} as a ratio to T_{TPW}, which is ‘known’ exactly.
- $u(T_{\mathrm{TPW}})$ is then the uncertainty of realisation ~ 40 µK (k = 1)

In future:

- Traceability to the joule is more complex than traceability to T_{TPW}
- Now the value of T_{TPW} is itself uncertain with an uncertainty (after re-definition) of close to 140 µK making a quadrature sum ~146 µK

For example:

- At 303 K in our recent measurements of $T - T_{90}$
  - $u(T)$ was ~ 150 µK.
  - $u(T)$ will increase to ~ 205 µK.

But notice that.:

- The uncertainty of any product $k_{\mathrm{B}}T$ or RT is unaffected

- ***Unlikely to have any major significance***

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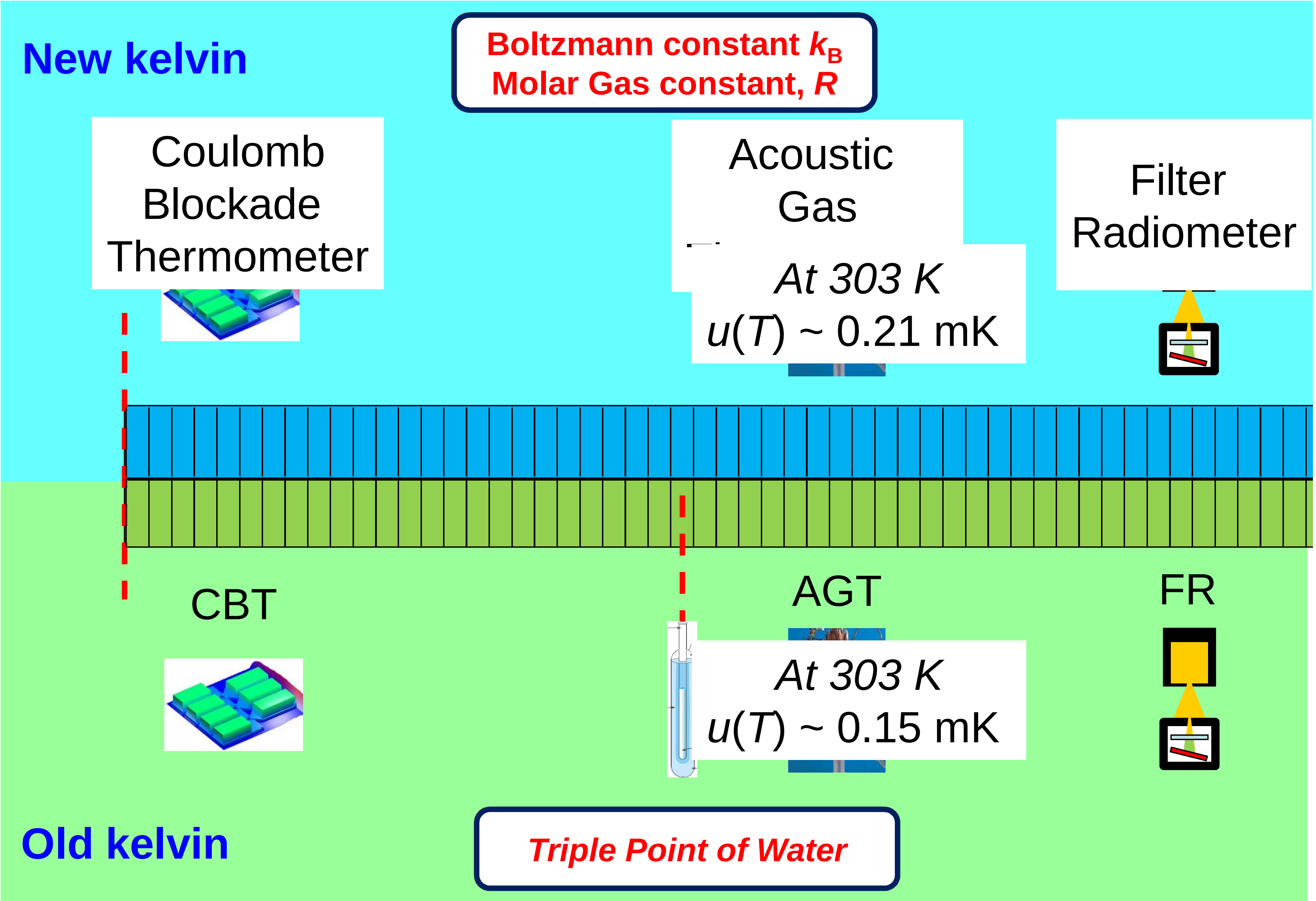


For primary thermometry $T >> T_{TPW}$

Currently two routes to traceability via Planck Law

Traceability to…	
kelvin	**electrical power**
$T_{unknown}$ deduced from a spectral radiance ratio to (say) T_{Cu}.	$T_{unknown}$ deduced from absolute spectral radiance (W sr^{-1} m^2)

In future

Traceability to…	
kelvin	**electrical power**
$u(T_{unknown})$ will be *increased* (negligibly) by an additional 140 µK (k = 1) of uncertainty in T_{TPW}.	$u(T_{unknown})$ will be *decreased* (negligibly) by an removal of uncertainty in k_B.

- ***Unlikely to have any major significance***

For primary thermometry $T \ll T_{TPW}$

For example, Coulomb Blockade Thermometer

Traceability to…
Ampere
T_{unknown} from $V_{1/2} \approx \frac{5.439 N k_B T}{e}$

In future

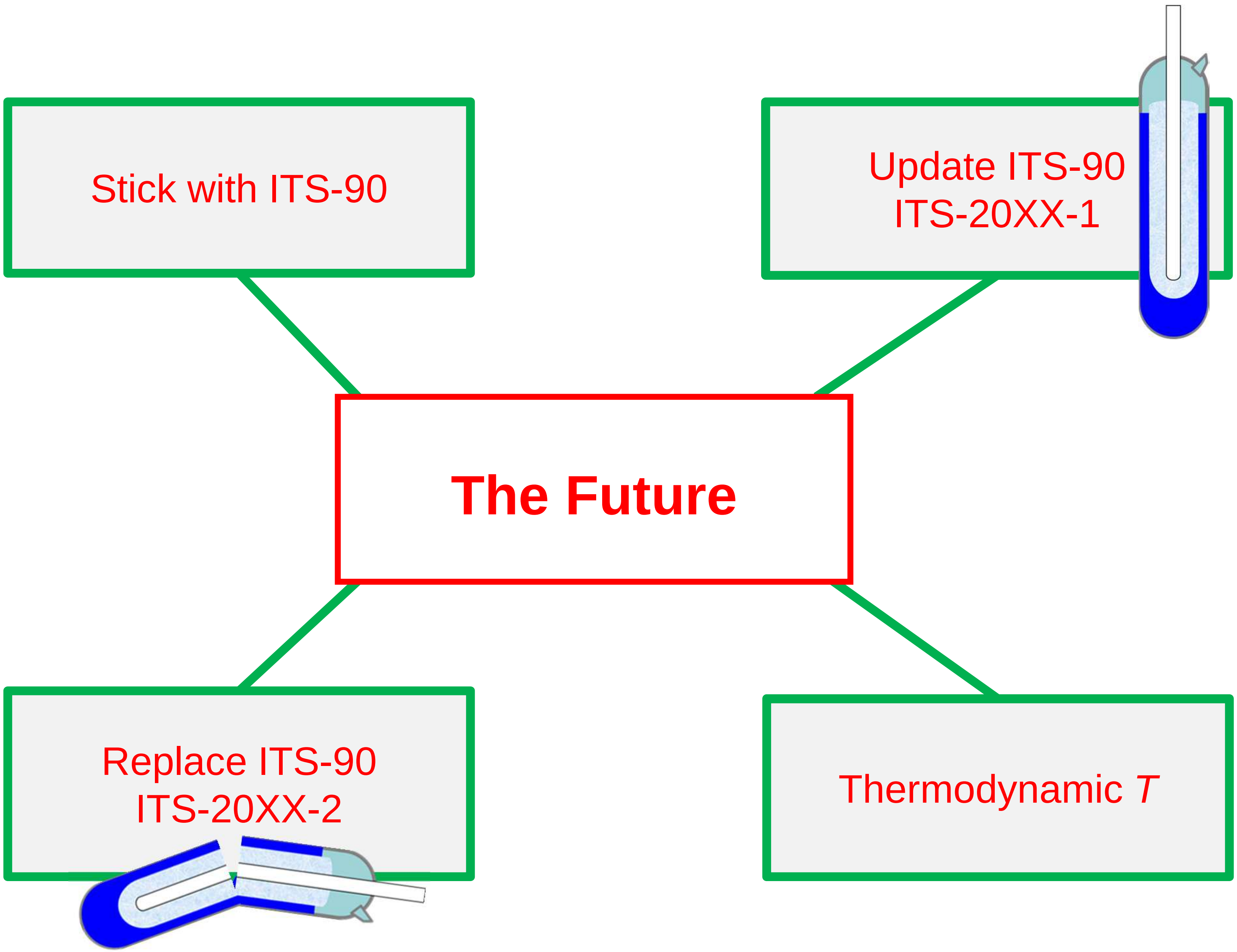
Traceability to…
kelvin
$u(T_{\text{unknown}})$ will be *decreased* (negligibly) by removal of uncertainty in k_B.

- ***Unlikely to have any major significance***

Rationale

Implementation

Longer Term Implications


Stick with ITS-90
Update ITS-90
ITS-20XX-1
The Future
Replace ITS-90
ITS-20XX-2
Thermodynamic *T*

Thermometry after 2018

From 2018, measurement of temperature will be fundamentally linked to the unit of energy, the joule

The Boltzmann constant

Measure the (speed of sound)^2...

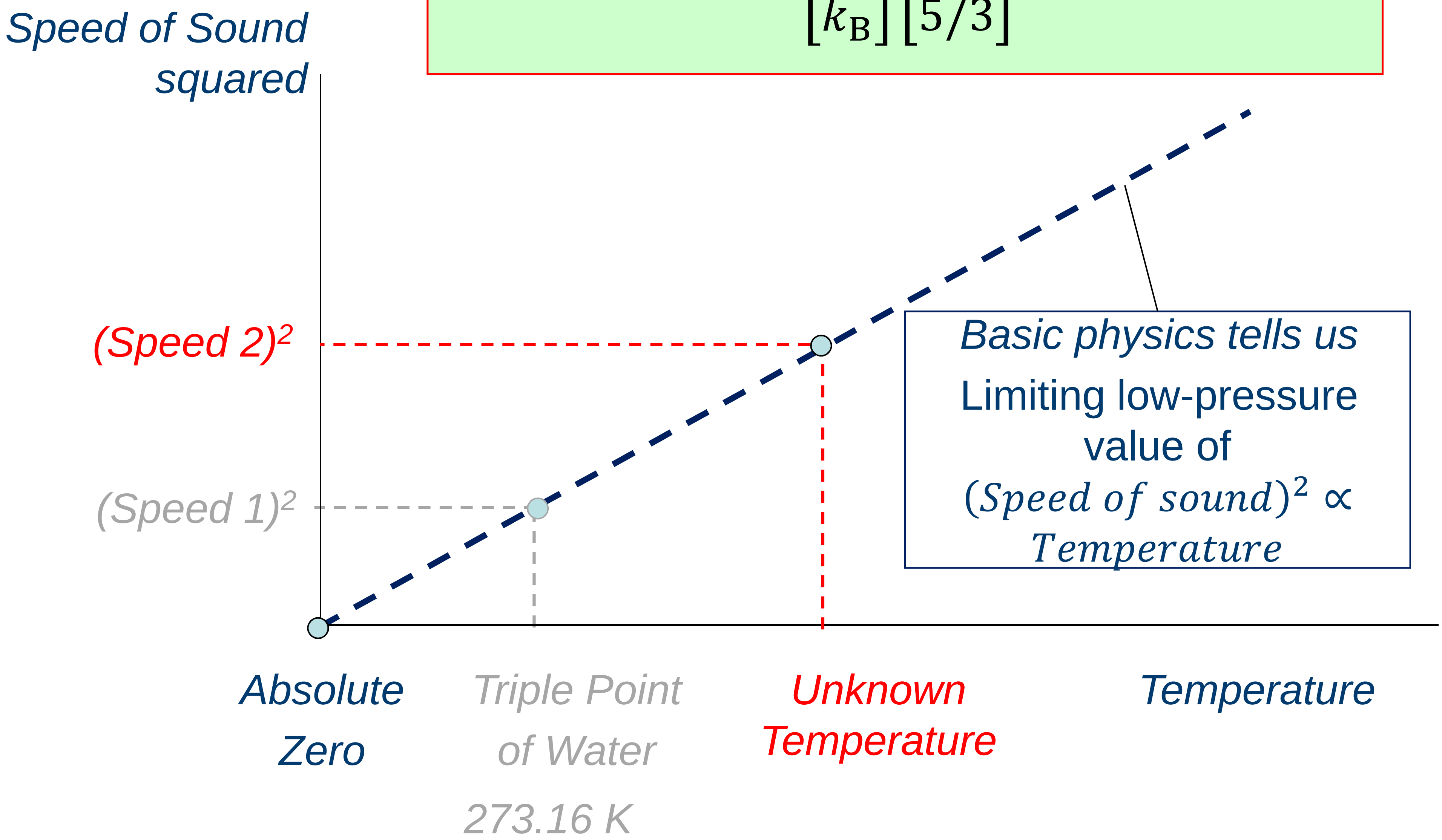
Mass of a molecule

To work out the absolute temperature in kelvins…

… in a pure gas of known molar mass

How to work out an unknown temperature after 2018

$$\left[\frac{1}{k_{\mathrm{B}}}\right]\left[\frac{m}{5/3}\right]$$



Practical Thermodynamic Thermometers?

- An atom-perfect nano-structured material with an artificially engineered electrical conductivity or tunnelling characteristic.

- Computers of sufficient power to model the electrical resistivity of a metal or semiconductor from first principles.
  - SPRT or thermistor would become a *primary* instrument.

- Photonic crystal interferometers with the possibility of primary self-calibration.

- Acoustic resonators that could act as super-accurate references – cheaper and more reliable than an SPRT.
  - Possible lower uncertainty than T_{90}

- Practical Johnson Noise Thermometer

- Something else that we can’t imagine!

All these devices are conceivable.
In 100 years time they may even be likely

The Distant Future….

- Everyone is happy ☺
- Everything is perfect ☺
- Thermodynamic Thermometers are used in every NMI!
- Practical Thermodynamic Thermometers will be here 'soon'.

- A new fixed-point is sent to three NMIs
  - Thermodynamic thermometer A in PBT reads 34.234 °C
  - Thermodynamic thermometer B in NLP reads 35.111°C
  - Thermodynamic thermometer C in NSIT reads 33.123°C

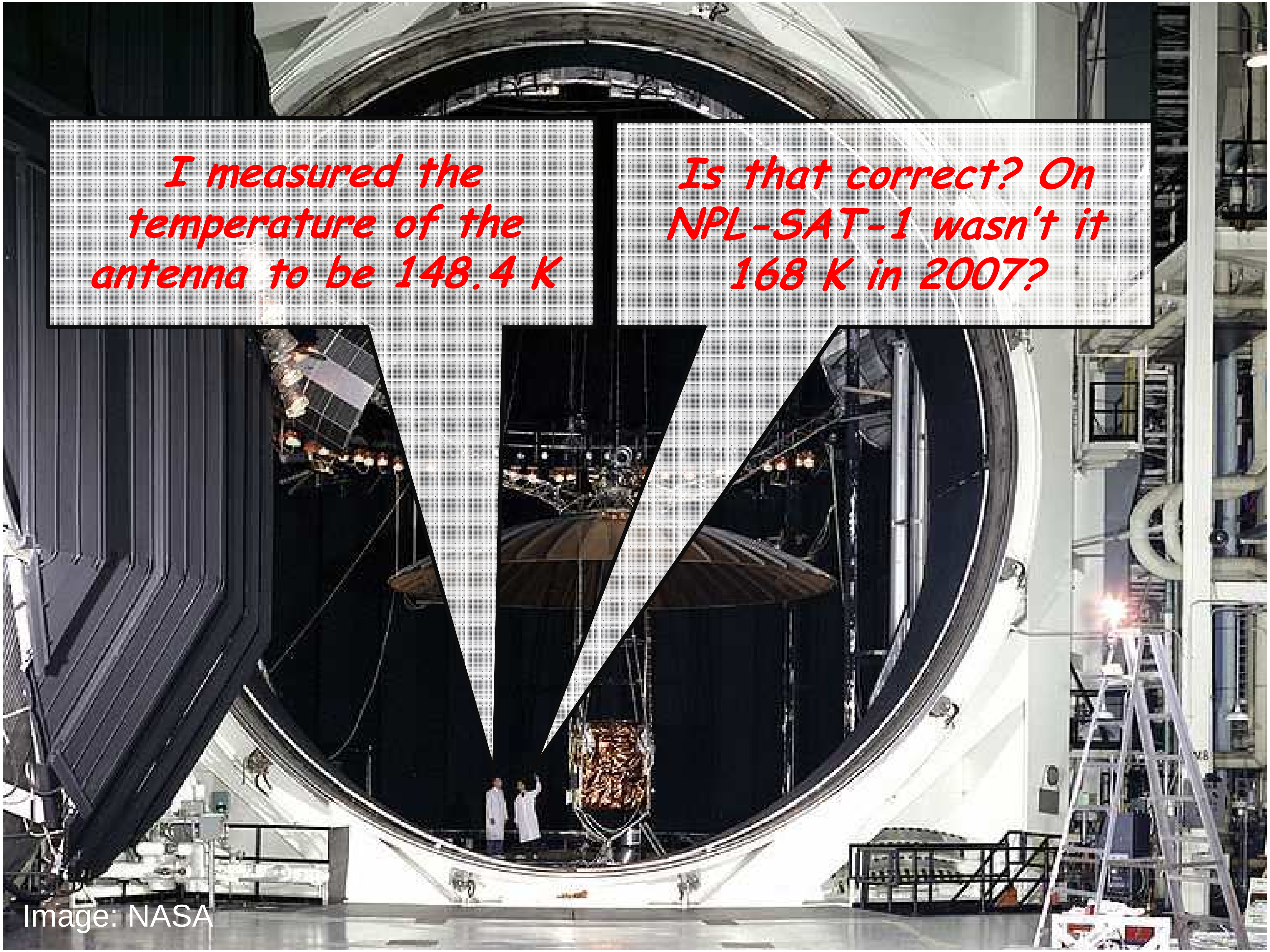
- To resolve these differences we need a third type of thermometer that is used for comparisons only and is super-precise and super stable.
- In a world of thermodynamic thermometers, we still need the equivalent of ITS-90 to enable reliable comparisons

For thermometery, it is almost always more important to agree on the temperature, than to be 'right'

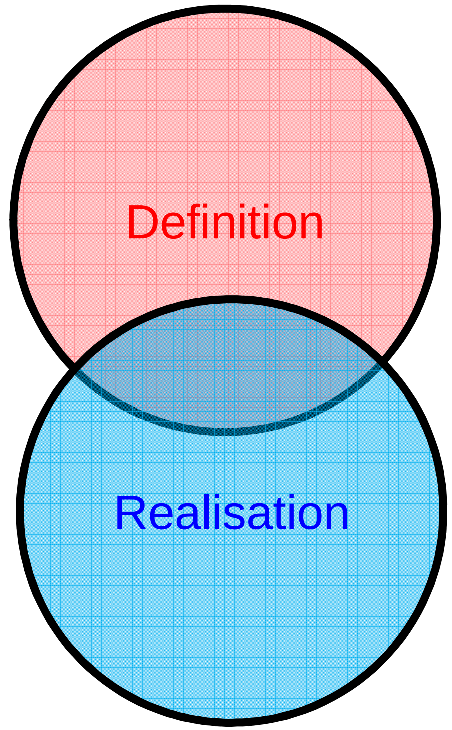
'Cooking' is more important than 'science'!

How will you know what the temperature is next year?

1. What’s the point?
2. The new SI
3. The new kelvin
4. What was the point again?


I measured the temperature of the antenna to be 148.4 K
Is that correct? On NPL-SAT-1 wasn't it 168 K in 2007?
Image: NASA

Summary



The kelvin redefinition:

- Fits well within the new model of the SI
- Separates what we mean by 'one kelvin', from how we realise it.
- Does not solve any problems we have today.
- Paves the way for future developments.

In short term:

- No negative consequences because of the widespread use of ITS-90

In the medium term :

- Questions about role and design of a replacement for ITS-90

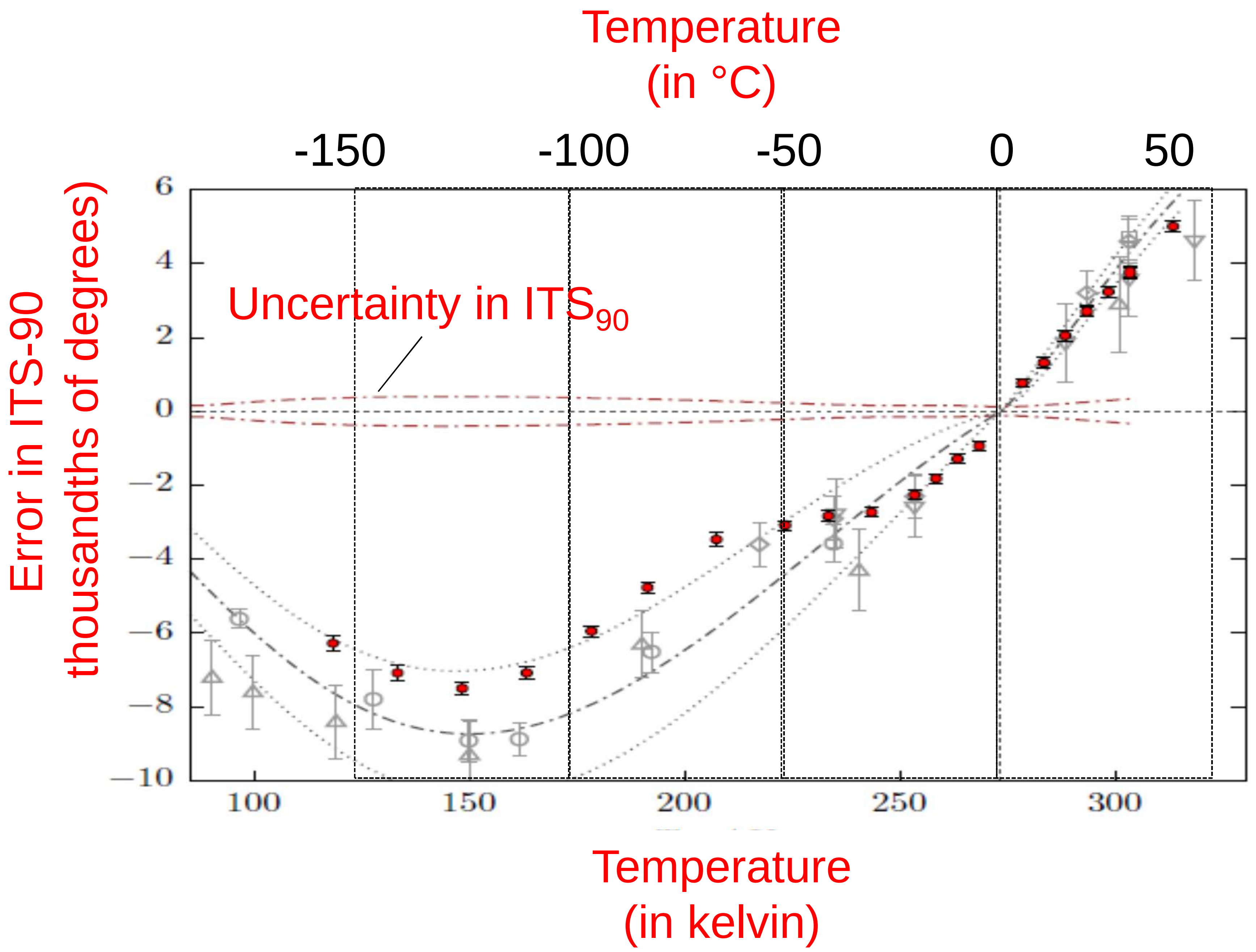
In the distant future:

- People will look back and ask why it took so long.
- But they will probably still be using something like ITS-90!

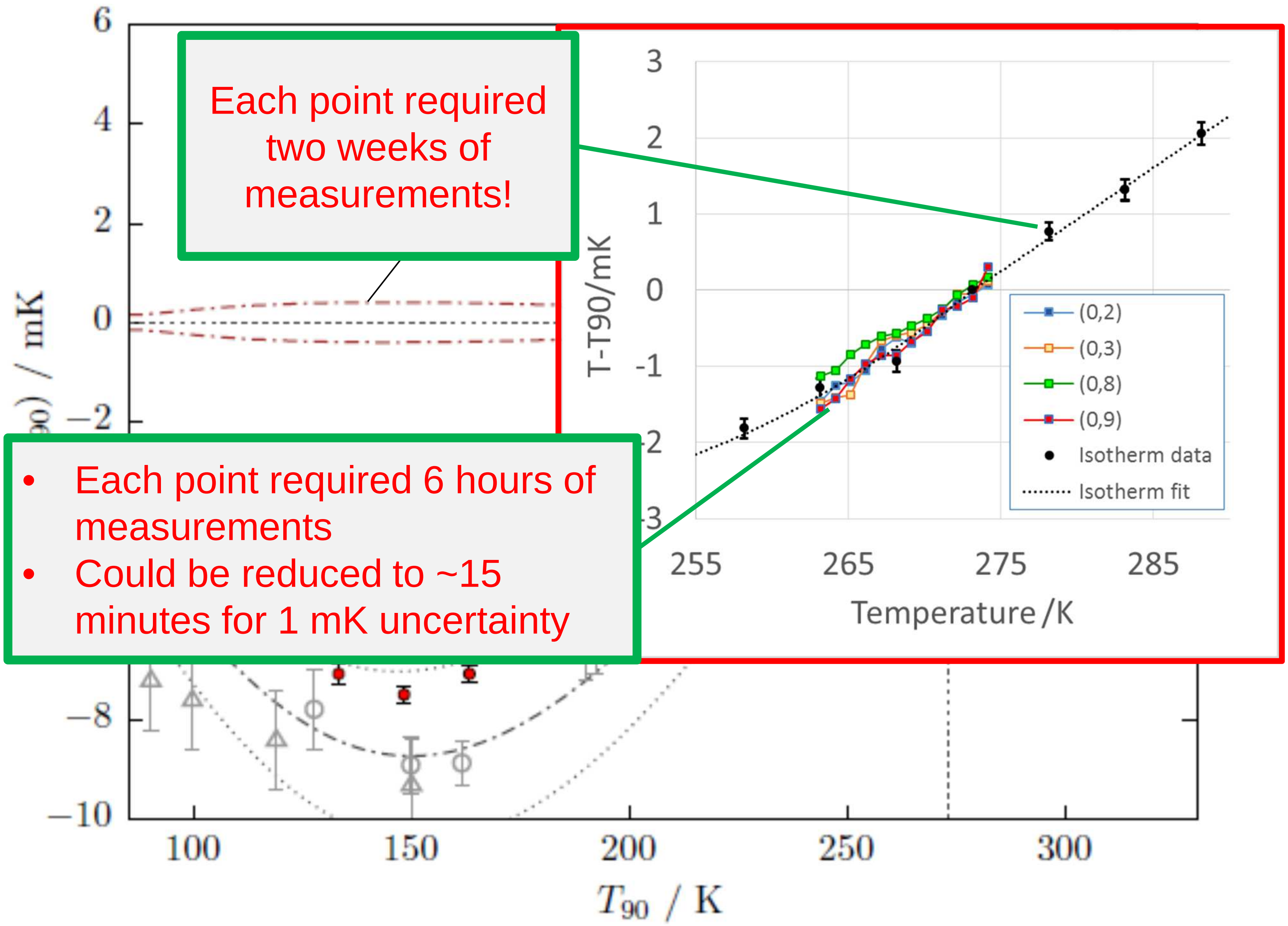

Precision Measurement…
…brings the world into focus
Except
cycles

Thank you

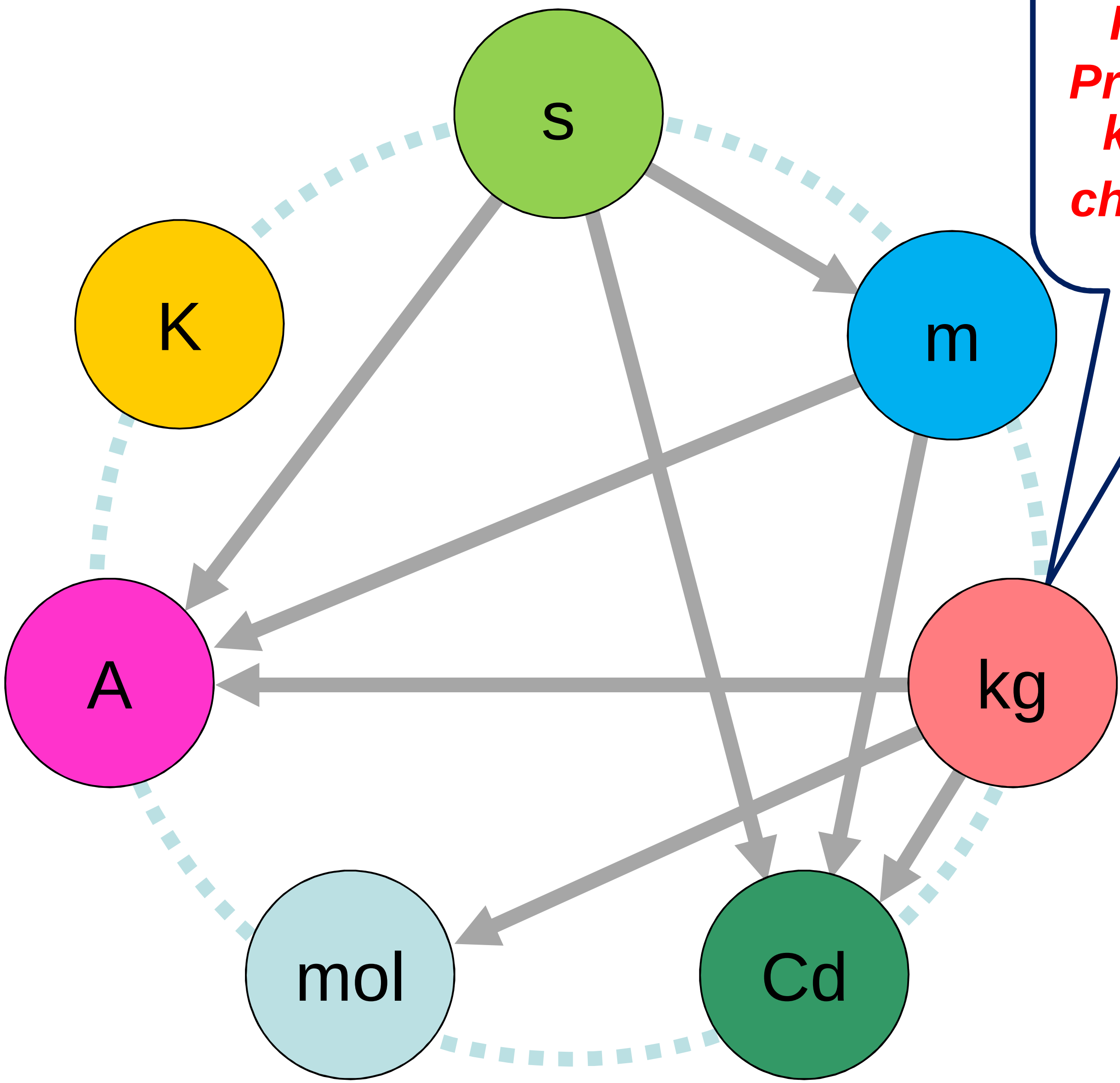
Errors in ITS-90



$T - T_{90}$ showing only uncertainty in T



The International System of Units

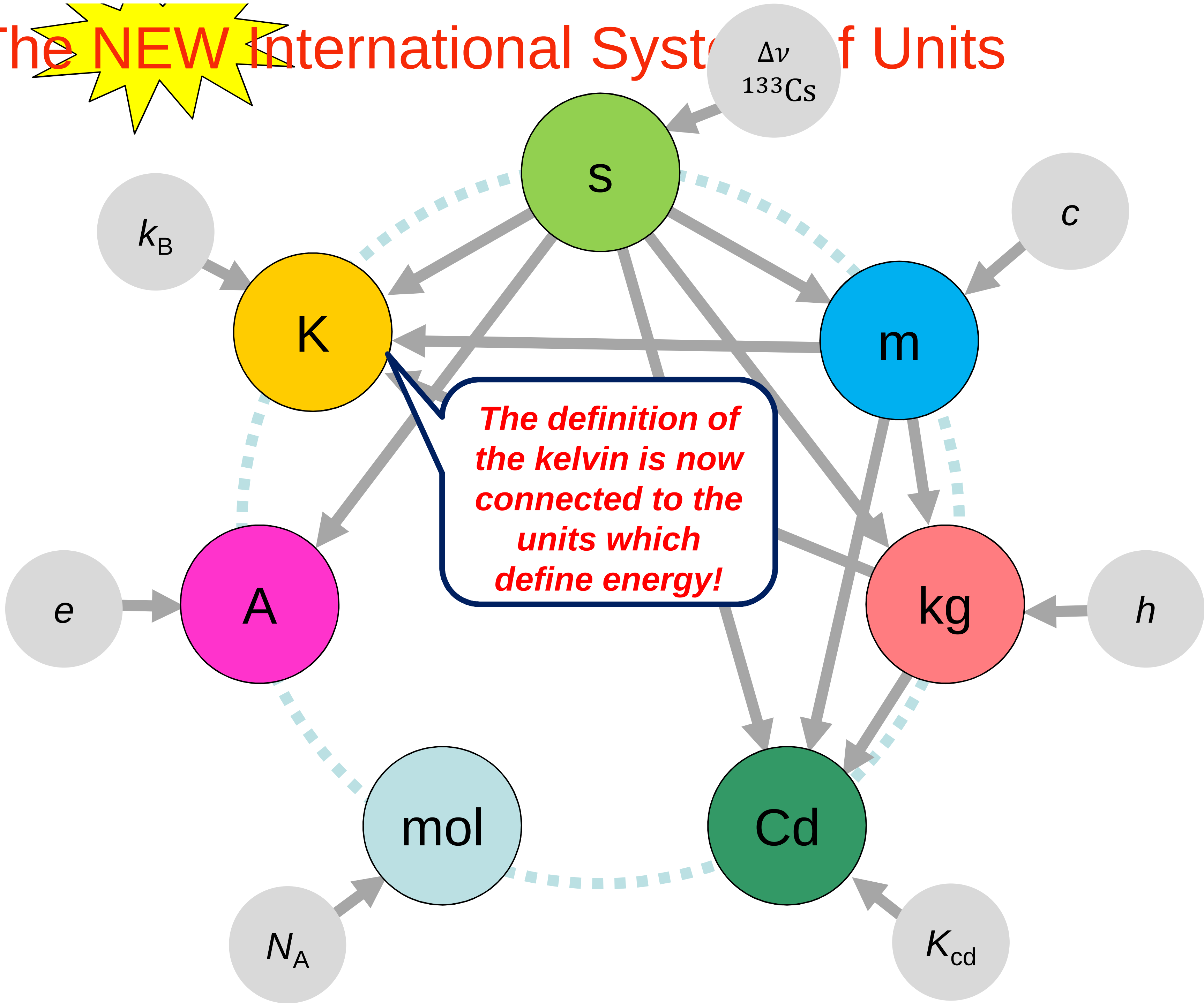


International Prototype of the kilogram, K***, is changing mass!***

The NEW International System of Units

The NEW International System of Units

The NEW International System of Units



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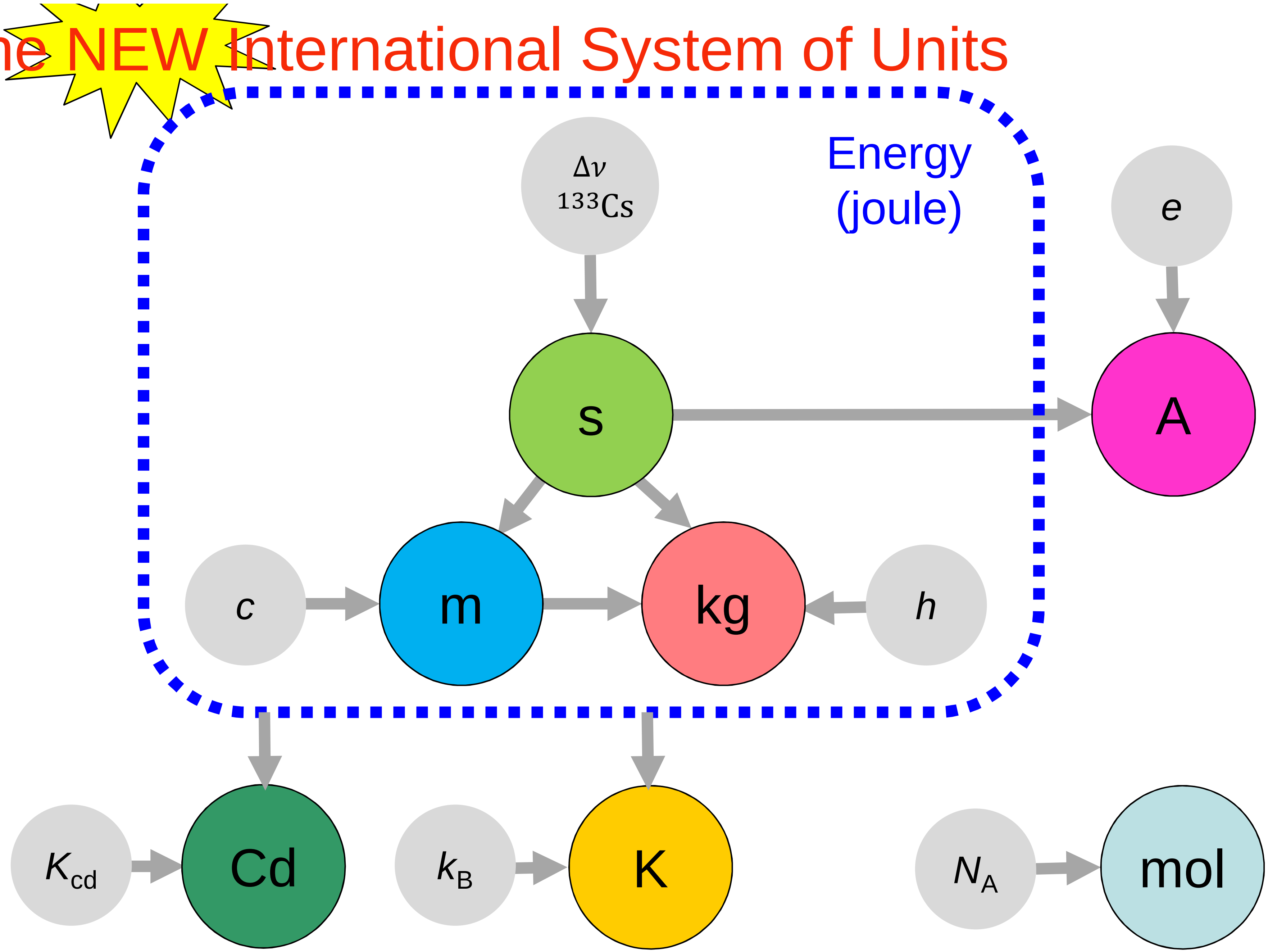
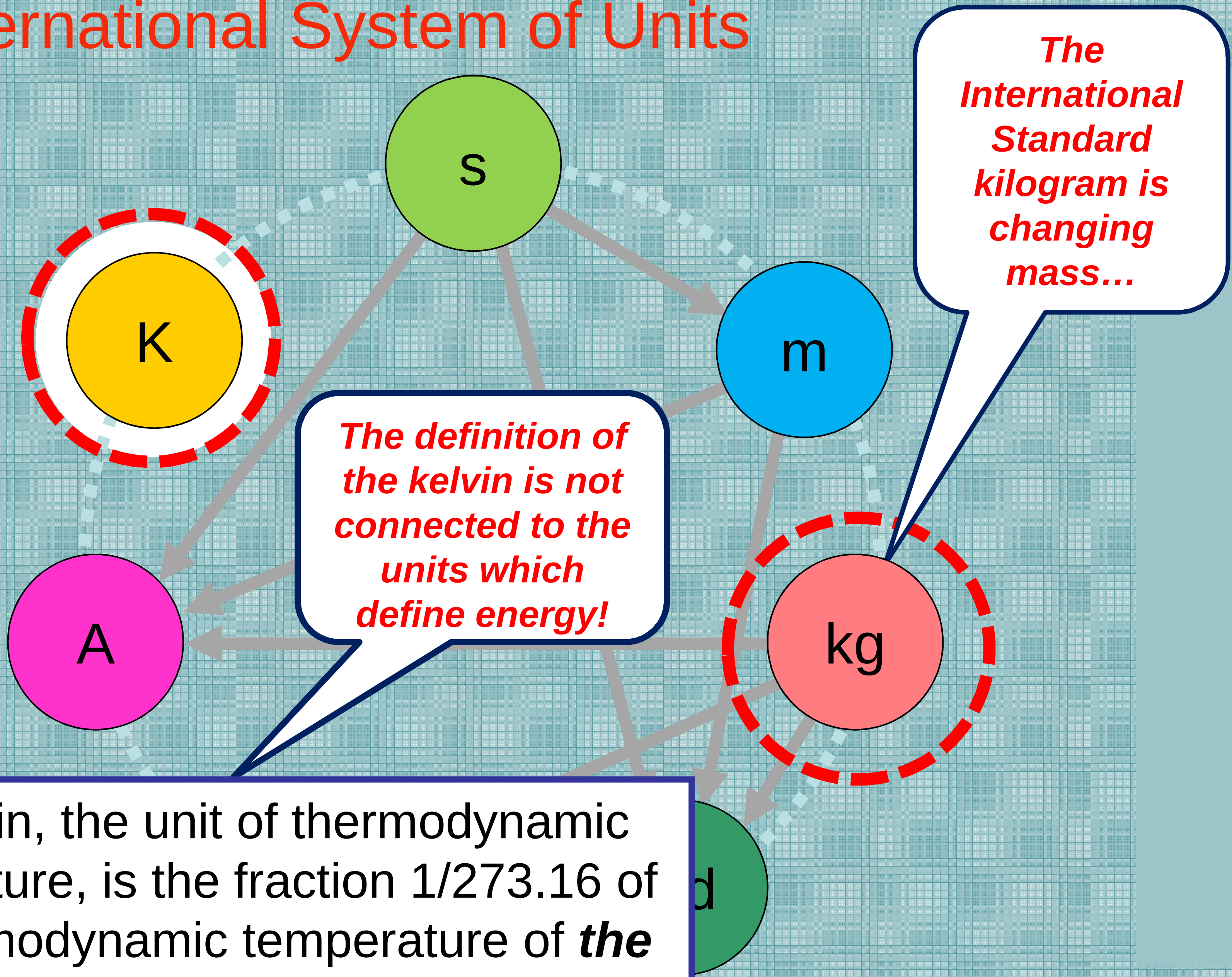
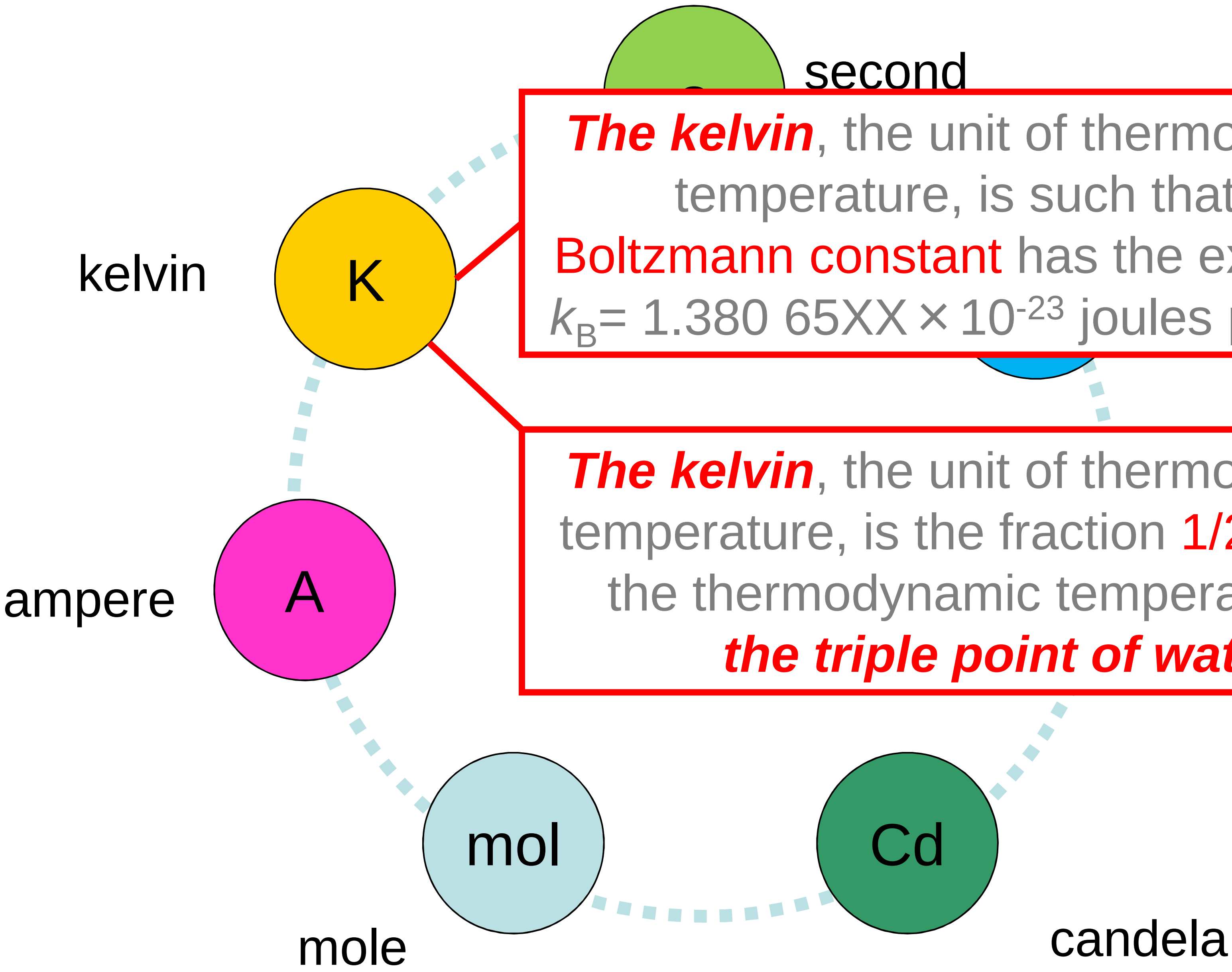


The International System of Units



The kelvin, the unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of ***the triple point of water***

The International System of Units



The kelvin, the unit of thermodynamic temperature, is such that the Boltzmann constant has the exact value k_B= 1.380 65XX × 10^{-23} joules per kelvin

The kelvin, the unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of ***the triple point of water***

An acoustic thermometer

From 2018, measurement of temperature will be fundamentally linked to the unit of energy, the joule

The Boltzmann constant

$$\frac{\ldots_3\, k_B T}{m}$$

Measure the (speed of sound)^2...

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