Bureau International des Poids et Mesures

Frequently Asked Questions

about the revision of the SI that came into force on 20 May 2019

(Updated 20 May 2019)

Q1: What has changed?

A1: The kilogram, kg, ampere, A, kelvin, K, and mole, mol, have new definitions, but they have been so chosen that at the moment of the change the magnitudes of the new units were indistinguishable from those of the old units.

Q2: So what was the point of changing to new definitions?

A2: Defining the kilogram in terms of fundamental physical constants ensures its long-term stability, and hence its reliability, which was previously in doubt. The new definitions of the ampere and kelvin are expected to significantly improve the accuracy with which electrical, and radiometric temperature measurements can be made. The impact on electrical measurements has been immediate: the most precise electrical measurements were already made using the Josephson and quantum Hall effects prior to the redefinition, and fixing the numerical values of the Planck constant h and the elementary electrical charge e in the new definitions of the units has led to exact numerical values for the Josephson and von Klitzing constants. This eliminates the previous need to use conventional electrical units rather than SI units to express the results of electrical measurements (see A14). The conversion factor between measured radiance and thermodynamic temperature (the Stefan-Boltzmann constant) is now exact with the present definitions of the kelvin and kilogram, leading to improved temperature metrology as technology improves. The revised definition of the mole is simpler than the previous definition, and it should help users of the SI to better understand the nature of the quantity "amount of substance" and its unit, the mole. All in all, the SI is now a better fit to the technology of this century.

Q3: What about the definitions of the second, s, metre, m, and candela, cd?

A3: The definitions of the second, s, metre, m, and candela, cd, have not changed, but the way the definitions are written was revised to make them consistent in form with the current definitions for the kilogram, kg, ampere, A, kelvin, K, and mole, mol.

Q4: What will happen to the IPK now that the revised SI has taken effect? Will it go to a museum where the general public can at last see it?

A4: There are no plans to change the storage conditions for the IPK. It will remain at the BIPM and it will not be on display for the general public. The IPK will retain a bit of metrological interest and therefore it will be monitored very sporadically in the future to avoid as much as possible any surface damage. Measurements of the mass stability of the IPK in the future may help us extrapolate its mass stability in the recent past.

Q5: Can I get my standard of mass calibrated in the same way as I did before 20 May 2019?

A5: You can continue sending your mass standard to your National Metrology Institute (NMI) for calibration or to a secondary calibration laboratory just as you did before. However, the traceability path that your NMI uses to link it to the SI kilogram has changed.

Indeed, the BIPM is organizing an ongoing comparison among primary realizations of the kilogram and a *consensus value* of the kilogram will be determined from it. National Metrology Institutes having a realization of the kilogram are requested to avail themselves of the *consensus value* when disseminating the unit of mass according to the new definition, until the dispersion in values becomes compatible with the individual realization uncertainties, thus preserving the international equivalence of calibration certificates and in accordance with the principles and agreed protocols of the CIPM Mutual Recognition Arrangement.

Member States not having realizations of the new definition of the kilogram have direct access to traceability to the same *consensus value* through the calibration services of the BIPM during the phase where the consensus value is used.

Q6: Once laboratories can realize the kilogram themselves, how can we be sure that inter-laboratory results are compatible?

A6: In the case of the kilogram, when the *consensus value* will no longer be needed, all laboratories will need to demonstrate traceability to the definition of the kilogram, which will be based on physical constants. Since it is always possible to underestimate an experimental uncertainty or just to make a mistake, laboratories that claim the smallest uncertainties will compare results periodically to assess compatibility with their peers. A basic mechanism for this already exists and is widely used in metrology. It is based on the CIPM Mutual Recognition Arrangement established in 1999.

Q7: Are NMIs also requested to avail themselves of a *consensus value* for the dissemination of the three other redefined units?

A7: No. The kilogram is a special case. Electrical units and the kelvin are mentioned in A14 and A8, below. As for the mole, there has been no change to previous practice.

Q8: Can I get my thermometer calibrated in the same way as I did before 20 May 2019?

A8: Yes. The new definition of the kelvin has not impacted the status of the widely-used ITS-90 and PLTS-2000 temperature scales. The Consultative Committee for Thermometry (CCT) has published information concerning immediate and future advantages of the new definition.

Q9: **In the SI the reference constant for the kilogram is the Planck constant *h*, with unit J s = kg m^2 s^{-1}. It would be much easier to comprehend if the reference constant had the unit of mass, the kg. Then we could say: "The kilogram is the mass of <*something*>", such as perhaps the mass of a specified number of carbon or silicon atoms. Would that not have been a better definition?**

A9: This is to some extent a matter of subjective judgement. However note that the reference constant used to define a unit does not *have* to be dimensionally the same as the unit (even though it may be conceptually simpler when this is the case). For a long time the SI has used several reference constants , each of which having a different unit to that being defined. For example, the metre is defined using as reference constant the speed of light *c* with unit m/s, not a specified length in m. This definition has not been found unsatisfactory. This practice first began in 1960, with the previous definition of the ampere which was based on the fixed value of a constant whose unit was kg m s^{-2} A^{-2}. (The present definition of the ampere is simpler.)

Although it may seem intuitively preferable to define the kilogram using a mass as the reference constant, using the Planck constant has other advantages. For example, now that both *h* and *e* are exactly known, both the Josephson and von Klitzing constants K_J and R_K are also exactly known, with great advantages for electrical metrology. (Physics tells us that we cannot fix both *h* and the mass of <*something*>, for instance the mass of a carbon 12 atom $m(^{12}C)$, without consequently redefining the second in a very impractical way.)

Q10: **Despite the answer to Q9 above, there are still people who question the wisdom of defining the kilogram by using *h* as a reference rather than by using $m(^{12}C)$. One of the arguments they use is that the Kibble[1] balance (KB) experiment to determine *h* uses a complex apparatus that is difficult to use and expensive to build, in comparison with the XRCD (x-ray crystal density) experiment to measure the mass of a silicon 28 atom, and hence the mass of a carbon 12 atom. What are the principal reasons for choosing *h* rather than $m(^{12}C)$ as the reference constant for the kilogram?**

A10: These are really two unrelated questions:

1. Why choose *h* rather than $m(^{12}C)$ as the reference constant for the kilogram?
2. Does the choice of *h* or $m(^{12}C)$ determine whether the kilogram will be realized in practice by a KB experiment or by the XRCD experiment?

1. Once the numerical value of a constant is given a fixed value, the constant need not, indeed cannot, be measured subsequently. For example, in 1983 when the SI was modified by making the speed of light in vacuum, *c*, the reference constant for the metre, the long history of measuring *c* abruptly ended. This was an enormous benefit to science and technology, in part because *c* enters into so many domains of science and technology that every time there was a change to the recommended SI value of *c*, the values of numerous constants and conversion factors related to *c*

[1] To recognize Bryan Kibble's invention of the watt balance

needed to be updated. The decision to define the numerical value of *c* as exact was obviously correct.

Similarly, *h* is the fundamental constant of quantum physics and consequently its SI value is used in many diverse fields of modern science and technology. In the past, changes to the recommended value of *h* as experiments improved were at best annoying and at worst confusing. The rationale for defining the numerical value of *h* was similar to that for defining *c*, but had the specific advantages in electrical metrology given in A2.

Of course $m(^{12}\text{C})$ is undeniably a constant and is undeniably important, especially for chemistry and the physics of atoms. This is because atomic weights (if you are a chemist), also known as relative atomic masses (if you are a physicist), are all based on $m(^{12}\text{C})$. Nevertheless, atomic weights do not depend on the definition of the kilogram and, of course, they have been unaffected by the new definition.

2. No. The choice of which reference constant is used to define the kilogram does not imply any particular method to realize the kilogram, and none is mentioned in Resolution 1 (2018). We do know that any realization must be traceable to *h* since *h* is the reference constant in the present definition of the kilogram. However, it is also known that $h/m(^{12}\text{C}) = Q$, where *Q* represents a product of exact numerical factors and experimentally-determined constants. The relative standard uncertainty of *Q* is less than 4.5×10^{-10} based on the current recommended values of the constants involved. An apparatus, such as the KB, which measures a 1 kg mass standard directly in terms of *h* (through electrical measurements made with quantum devices) and auxiliary measurements of length and time can be used to realize the kilogram. However, an experiment that measures a 1 kg mass standard in terms of $m(^{12}\text{C})$, as in the XRCD project, also has the potential to realize the kilogram. This is because $m(^{12}\text{C})Q = h$, and thus the price to pay for arriving at *h* by way of $m(^{12}\text{C})$ is the added uncertainty of *Q*, which is negligible in the context of realizing the present definition.

Q11: Have the seven base quantities and base units of the SI changed?

A11: No. The seven base quantities (time, length, mass, electric current, thermodynamic temperature, amount of substance, luminous intensity) and corresponding base units (second, metre, kilogram, ampere, kelvin, mole, candela) have remained unchanged.

Q12: Have the 22 coherent derived units with special names and symbols changed?

A12: No, the 22 coherent derived units with special names and symbols have remained unchanged in the SI.

Q13: Have the names and symbols of the multiple and sub-multiple prefixes (kilo for 10^3, milli for 10^{-3}, etc.) changed in the present SI?

A13: No, the names and symbols for the prefixes have remained unchanged.

Q14: Have the magnitudes of any of the units changed?

A14: No. So-called "continuity conditions" were established before the transition to help ensure that there would be no change in magnitude of any of the SI base units, and hence no change in any units derived from the base units.

(There is a small exception involving electrical units: since 1990 until May 2019, the electrical units used in practice were based on conventional values for the Josephson constant and the von Klitzing constant rather than on their SI definitions at the time. This led to small offsets between the conventional and the SI values. The revision of the SI has brought the practical electrical units back into the SI. On 20 May 2019 there was a one-time change of + 0.1 parts per million (ppm) for voltage values and of + 0.02 ppm for resistance values when expressed in the SI units.)

Q15: How can you fix the value of a fundamental constant like *h* to define the kilogram, and *e* to define the ampere, and so on? How did you know what value to fix them to? What if it emerges that you have chosen the wrong value?

A15: We have not fixed – or changed – the <u>*value*</u> of any constant that we use to define a unit. The values of the fundamental constants are constants of nature and we have only fixed the <u>*numerical value*</u> of each constant when expressed <u>*in its SI unit*</u>. By fixing its numerical value we define the magnitude of the unit in which we measure that constant at present.

Example: If c is the *value* of the speed of light, $\{c\}$ is its *numerical value*, and $[c]$ is the *unit*, so that

$$c = \{c\}\ [c] = 299\ 792\ 458\ \text{m/s}$$

then the value c is the product of the number $\{c\}$ times the unit $[c]$, and the value never changes. However the factors $\{c\}$ and $[c]$ may be chosen in different ways such that the product c remains unchanged.

In 1983 it was decided to fix the number $\{c\}$ to be exactly 299 792 458, which then defined the unit of speed $[c]$ = m/s. Since the second, s, was already defined, the effect was to define the metre, m. The number $\{c\}$ in the new definition was chosen so that the magnitude of the unit m/s was unchanged, thereby ensuring continuity between the new and old definitions of the units.

Q16: OK, you actually have only fixed the <u>*numerical value*</u> of the constant expressed in its <u>*unit*</u>. For the kilogram, for example, you have chosen to fix the numerical value $\{h\}$ of the Planck constant expressed in its unit $[h]$ = kg m^2 s^{-1}. But the question remains: suppose a new experiment suggests that you have chosen a wrong numerical value for $\{h\}$, what then?

A16: Now that we have made the change, the mass of the international prototype of the kilogram (the IPK), which defined the kilogram from 1889 until 20 May 2019, will have to be determined by experiment. If we have chosen a "wrong value" it simply means that the new experiment will tell us that the mass of the IPK is not exactly 1 kg.

This situation would only affect macroscopic mass measurements; the masses of atoms and the values of other constants related to quantum physics would not be affected. Continuing with the definition of the kilogram agreed in 1889 would continue the practice of using a reference quantity (i.e. the mass of the IPK) that we cannot be sure is not changing with time compared to a true invariant such as the mass of an atom or the Planck constant.

There has been much debate over the years about how much the mass of the IPK might be changing with respect to the mass of a true physical constant. The advantage of the new definition is that we are certain that the reference constant used to define the kilogram is a true invariant.

Q17: Each of the fundamental constants used to define a unit has an uncertainty; its value is not known exactly. But you have fixed its numerical value exactly. How can you do that? What has happened to the uncertainty?

A17: The previous definition of the kilogram fixed the mass of the IPK to be one kilogram exactly with zero uncertainty, $u_r(m_{IPK}) = 0$. The Planck constant, before the revision of the SI, was experimentally determined, and had reached a relative standard uncertainty of 1.0 part in 10^8, $u_r(h) = 1.0 \times 10^{-8}$.

Now, the value of h is known exactly in terms of its SI unit so that $u_r(h) = 0$. But the mass of the IPK needs to be experimentally determined, and its initial value has a relative uncertainty of $u_r(m_{IPK}) = 1.0 \times 10^{-8}$. Thus the uncertainty is not lost in the new definition, but it moves to become the uncertainty of the previous reference that is no longer used, as in the table below.

Constant used to define the kilogram	*Previous SI status uncertainty*	*Current SI status uncertainty*
mass of the IPK, $m(\mathcal{K})$	exact 0	expt. 1.0×10^{-8}
Planck constant, h	expt. 1.0×10^{-8}	exact 0

Q18: The unit of the Planck constant is the unit of action, J s = kg m^2 s^{-1}. How does fixing the numerical value of the Planck constant define the kilogram?

A18: Fixing the numerical value of h actually defines the unit of action, J s = kg m^2 s^{-1}. But if we have already defined the second, s, to fix the numerical value of the caesium hyperfine transition frequency $\Delta\nu_{Cs}$, and the metre, m, to fix the numerical value of the speed of light in vacuum, c, then fixing the magnitude of the unit kg m^2 s^{-1} has the effect of defining the unit kg.

Q19: Are not the current definitions of the base units in the Revised SI circular definitions, and therefore unsatisfactory?

A19: No, they are not circular. A circular definition is one that makes use of the result of the definition in formulating the definition. The words for the individual definitions of the base units in the current SI specify the *numerical value* of each chosen reference constant to define the corresponding unit, but this does not make use of the result to formulate the definition.

Q20: Can we still check the consistency of physics now that we have fixed the values of all the fundamental constants?

A20: We have not fixed the values of all the fundamental constants, only the *numerical values* of a small subset and combinations of the constants in this subset. This has had the effect of changing the definitions of the units, but not the equations of physics, and it cannot prevent researchers from checking the consistency of the equations.

Q21: Now the physical constants *c*, *h* and *e* all have fixed numerical values. But doesn't this fix the value of the fine-structure constant, which must not be given a fixed value?

A21: No. The value of the fine-structure constant continues to be determined by experiment. In the SI, the fine-structure constant has always depended on c, h, e and μ_0. The fourth constant is the vacuum magnetic permeability, which previously defined the ampere but now is determined experimentally from a measurement of the fine-structure constant.