

Bureau International des Poids et Mesures

Consultative Committee for Units (CCU)

Report of the 25th meeting
(21-23 September 2021)

to the International Committee for Weights and Measures



Comité international des poids et mesures

LIST OF MEMBERS OF THE CONSULTATIVE COMMITTEE FOR UNITS

as of 21 September 2021

President

Prof. J. Ullrich, President of the PTB, Vice-President of the CIPM

Executive Secretary

Dr M. Stock, International Bureau of Weights and Measures [BIPM]

Members

Centro Español de Metrología [CEM], Madrid

Federal Agency on Technical Regulating and Metrology [Rosstandart], Moscow

Federal Institute of Metrology METAS [METAS], Bern-Wabern

Korea Research Institute of Standards and Science [KRISS], Daejeon

Laboratoire National de Métrologie et d'Essais [LNE], Paris

National Institute of Metrological Research/Istituto Nazionale di Ricerca Metrologica [INRIM], Turin

National Institute of Metrology [NIM], Beijing

National Institute of Standards and Technology [NIST], Gaithersburg

National Metrology Institute of Japan, AIST [NMIJ/AIST], Tsukuba

National Physical Laboratory [NPL], Teddington

National Research Council of Canada [NRC], Ottawa

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig

Prof. M. Himbert, personal member

Dr T.J. Quinn CBE FRS, personal member

Prof. I.M. Mills, OBE FRS, honorary member

The Director of the International Bureau of Weights and Measures [BIPM], *ex officio* member

Official Observer

National Scientific Centre "Institute of Metrology" [NSC IM], Kharkov

Liaisons

Committee on Data for Science and Technology [CODATA Task Group on Fundamental Constants]

International Astronomical Union [IAU]

International Commission on Illumination [CIE]

International Commission on Radiation Units and Measurements [ICRU]

International Electrotechnical Commission [IEC]

International Federation of Clinical Chemistry and Laboratory Medicine [IFCC]

International Mathematical Union [IMU]

International Organization for Standardization [ISO]

International Organization of Legal Metrology [OIML]

International Union of Pure and Applied Chemistry [IUPAC]

International Union of Pure and Applied Physics [IUPAP]

1. OPENING OF THE MEETING

The twenty-fifth meeting of the Consultative Committee for Units (CCU) was held online, from 21 to 23 September 2021.

The following were present: A. Balsamo (INRIM), S. Bize (LNE-SYRTE), P. Blattner (METAS), G. Brida (INRIM), M. Brown (NRC), R.J.C. Brown (NPL), C.W. Clark (NIST), F. Fang (NIM), D. Flater (NIST), B. Güttler (PTB), K. Hosaka (NMIJ/AIST), A. Kharchenko (NSC IM), E. Korzinin (VNIIM), M. Krystek (PTB), A.Y. Kuzin (VNIIMS), E. Lazarenko (Rosstandart), Y. Lin (NIM), G. Macdonald (NRC), E. Massa (INRIM), M.J.T. Milton (BIPM Director), P. Mohr (NIST), P. Neyezhnikov (NSC IM/CIPM member), F. Piquemal (LNE), E. Prieto Esteban (CEM), Y. Shimizu (NMIJ/AIST), J. Ullrich (CIPM/CCU President), I. Yang (KRISS), M. Yasuda (NMIJ/AIST), D.-H. Yu (KRISS), J. Zhang (NIM).

Liaisons: T. Bergen (CIE), N. Capitaine (IAU), C. Draghici (ISO), P. Gillery (IFCC), I. Godinho (IUPAP), H. Holden (IMU), R. Lapuh (OIML), R. Marquardt (IUPAC), D. Newell (CODATA-TGFC), T. Otto (ICRU), K. Pachucki (CODATA-TGFC), L. Pendrill (ISO), W. Philipps (IUPAP), P. Sebellin (IEC), E. Shirley (IUPAP), E. Tiesinga (CODATA-TGFC).

CIPM members and Consultative Committees Presidents: F.V. Bulygin, I. Castelazo (CCL President), N. Dimarcq (CCTF President), H. Laiz (CCAUV President), W. Louw (CIPM President), M.L. Rastello (CCPR President), P. Richard (CCM President), G. Rietveld (CEM President), M. Sené (CCRI President), A. Steele, T. Usuda (CIPM Secretary).

Personal members: M. Himbert (LNE-Cnam), T.J. Quinn (BIPM Emeritus Director).

Invited guests: C.J. Bordé (Académie des Sciences / CNRS), S. Karshenboim (Ludwig-Maximilians-Universität, Faculty of Physics), P. Quincey (retired; formerly NPL), C. Salomon (LKB).

Also present from the BIPM: H. Fang (CCM Executive Secretary), V. Gressier (CCRI Executive Secretary), G. Panfilo (CCAUV and CCL Executive Secretary), S. Picard (CCT Executive Secretary and KCDB Coordinator), M. Stock (CCU and CCEM Executive Secretary), P. Tavella (CCTF Executive Secretary), J. Viallon (CCPR Executive Secretary).

Prof. J. Ullrich opened the meeting at 12:00 UTC and welcomed all participants. He thanked all at the BIPM and especially Dr M. Stock for helping with the preparation of the meeting at this difficult time during the pandemic. Prof. Ullrich went on to state that, unfortunately, because of pandemic this would be a video conference and he noted that this was particularly difficult for the CCU because this was a committee that required in-depth discussion on the topics it addressed. In addition, Prof. Ullrich noted that the video conference format meant that there was a shorter time for discussion: only three slots of two hours rather than the normal two full days.

Because of this time restriction and the video conference nature of the meeting the CCU Strategy Working Group, who had met in January 2021, had suggested that the CCU should not try to come to conclusions on controversial issues at this meeting because there would not be time for sufficient discussion. Prof. W. Philipps asked Prof. Ullrich what the definition of a controversial issue was. Prof. Ullrich replied that these were items about which there was no consensus. Prof. Ullrich went on to introduce the meeting and talked about the achievements since the last CCU which had of course included the implementation of the revised SI. He noted that much consensus was achieved but not everything had been resolved. Prof. Ullrich went on to list the items on which there was currently no agreement: the definition of some core metrological terms, how to treat the radian and dimensionless quantities in the SI, and how the SI should evolve in the future. He observed that many of these issues would be discussed at this meeting.

1.1 News from the BIPM

Dr M. Milton welcomed all participants on behalf of the BIPM. He noted recent developments which members may have been unaware of. There were now 63 Member States and 39 Associates of the CGPM. Earlier in the year Estonia became a Member State, and the Kingdom of Cambodia became an Associate of the CGPM. GULFMET had become a full member regional metrology organization (RMO) of the Joint Committee of the Regional Metrology Organizations and the BIPM (JCRB), the sixth RMO to do so. Dr Milton noted that World Metrology Day in 2021 had focused on health, not least because of the ongoing pandemic, and had received extremely good engagement from all parties. Dr Milton observed that the 2022 World Metrology Day would be in collaboration with COOMET and would most likely focus on some aspect of digitalization. Dr Milton told participants about the BIPM's new e-learning platform that was accessible through the BIPM website. He observed that the e-learning platform was complementary to the ongoing capacity building activities at the BIPM, which had continued throughout the pandemic. Since January there had been engagement with 1200 people in the NMI/DI community and, particularly importantly, 600 people in the accreditation community. Dr Milton reviewed several activities at the BIPM related to the digitalization agenda. In particular, he highlighted the new XML version of the SI brochure which was nearly complete. When complete it would be possible from this XML file, via middleware, to generate exactly the same PDF or HTML file as the SI brochure. The XML version would also be the vehicle to allow machine readability and to which metadata and persistent identifiers could be added.

Dr Milton reported that new BIPM APIs (application programming interfaces) were available for both the key comparison database (KCDB) (which was now fully launched and had already seen NMI users taking advantage of this) and the BIPM time department. APIs for the BIPM time department were still at the beta testing stage but it was already obvious that this approach provided greater opportunity for services being delivered to NMIs and greater access to the data held at the BIPM.

1.2 Approval of the agenda, appointment of the rapporteur

Prof. Ullrich asked for the agenda to be approved, mentioning that there would be a new item under agenda point 4 associated with the consensus value for the kilogram. In the event, some of the items at the start of the meetings were taken in slightly different order to the published agenda.

Prof. Ullrich proposed Dr R. J. C. Brown as the rapporteur for the meeting and Dr R. Brown accepted, noting that recording the meeting made preparation of the meeting report much easier.

2. NEWS FROM THE CIPM

Prof. Ullrich reported on news from the CIPM. INRIM had been approved as a member to the CCU by the CIPM and NSC-IM, Ukraine, had been approved as an observer to the CCU. He noted that NSC-IM had submitted a membership request that needed to be discussed later. Prof. Ullrich added that the International Mathematical Union (IMU) had been accepted as liaison organization to the CCU.

A CIPM decision had allowed Consultative Committees to proceed online during the pandemic and CIPM-D-01 had been updated accordingly. Prof. Ullrich noted that the CIPM Task Group on Unit had been closed as it had completed its tasks and in its place the CIPM approved formation of the CCU Working Group on Core Metrological Terms (CCU WG-CMT) and its terms of reference. The

chairman of the working group was Prof. P. Neyezhnikov. Prof. Ullrich noted that Prof. Neyezhnikov was also the CIPM representative on the Joint Committee for Guides in Metrology (JCGM) and that this provided a very good, structured feedthrough mechanism for information from the working group. Prof. Ullrich noted that there had been a CIPM decision on a proposal to expand the range of SI prefixes and a decision on the questionnaire to be sent to stakeholders of the SI regarding the revision of the SI. It was also noted that a CIPM Task Group on the Digital SI had been established and this was supported by an expert working group of NMI members. There had been agreement on inclusion of digitalization in the BIPM work programme in the future.

Prof. Ullrich recalled that the CIPM had established a sub-committee on strategy to be chaired by the CIPM president Dr W. Louw. It was noted that the remit and terms of reference of this strategy group may be expanded in future and the consequences of this would be discussed in this meeting under agenda item 10.1. Prof. Ullrich noted that one of the consequences of this strategy had already been to establish a sectoral task group on climate change and the environment driven by the outputs of the CIPM report on evolving needs in metrology. Prof. Ullrich stated that this report had led to several draft resolutions for the 27th meeting of the CGPM (2022). Prof. Ullrich noted that all these items would be discussed later in the current meeting.

3. CCU PRESIDENT'S REPORT

Since Dr Milton had reported news from the BIPM previously, Prof. Ullrich moved on to provide the CCU President's report. Prof. Ullrich started by reviewing the decisions of the 24th CCU meeting, which had all been completed. He discussed the actions of the 24th CCU meeting, which he observed had mostly been done. The remaining actions had all been started but had been delayed by the pandemic. The remaining actions all related to the CCU WG-CMT and would be covered to some extent as the meeting progressed. Prof. Ullrich noted that member organizations and liaison organizations had been asked to provide their input to the work on core metrological terms and dimensionless quantities. Prof. Ullrich stated that no important suggestions or requests for corrections of the SI Brochure had been received.

Prof. Ullrich reported that the CCU Strategy Working Group had met in January 2021. One of the topics that had been discussed was the CCU WG-CMT and as a result Prof. Ullrich had asked Prof. Neyezhnikov to hold a further meeting to try and find consensus on the definitions discussed. Prof. Ullrich reminded participants again that the CCU Strategy Working Group had recommended that if it was not possible to find consensus at this on-line meeting then further discussion would be deferred to the next in person meeting of the CCU. Prof. Ullrich stated that the other topics discussed in the CCU Strategy Working Group would be raised at this meeting. He mentioned that one of the topics discussed at the CCU strategy working group was on the distinction between base and derived units, but it was decided that this would not be discussed at the current CCU meeting. There had been an open discussion on future topics for the CCU. One topic that had been raised was the status of the mole and the role of counting quantities within the SI. It was proposed that this was part of a wider discussion of future themes for the CCU to consider and would be taken under agenda point 10.3.

4. COMMENTS ON WRITTEN REPORTS FROM THE CONSULTATIVE COMMITTEES

There were no questions on the written reports from the consultative committees. Prof. Ullrich noted that the Consultative Committee for Length (CCL) and the Consultative Committee for Ionizing Radiation (CCRI) have already got digitalization work on their agendas, reflecting the aspirations of the CIPM. He also noted that the Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM) was in discussion about quantized measurements and in particular quantities related to counting, and this would be discussed later.

4.1 Report on the status of the planned redefinition of the second

Dr N. Dimarcq presented the work of the Consultative Committee for Time and Frequency (CCTF) related to the planned redefinition of the second. He reported that the CCTF had four 'hot topics' of discussion: the redefinition of the SI second (which would be discussed here); leap seconds in Coordinated Universal Time (UTC) and building a consensus for a continuous timescale; promoting the mutual benefit of UTC and Global Navigation Satellite Systems (GNSS); and sharing resources to improve international timekeeping. Dr Dimarcq mentioned the discussions that had occurred in the two sessions of the CCTF meeting, that had been held online during the pandemic, and the analysis of the more than 200 replies that had been received to an online questionnaire on these hot topics. The work so far had resulted in a proposal for two draft resolutions to the CGPM in 2022, one on the use and future development of UTC and the other on the future redefinition of the second. The CCTF had created three subgroups to consider different aspects of the redefinition of the second. Importantly several mandatory criteria had been identified, which must be achieved before redefinition, and also a number of ancillary conditions, which must be in progress at the time of redefinition. For each criterion a target is specified. As a result, the CCTF had specified three schedules for the redefinition of the second with the decision for redefinition being taken at either the CGPM in 2026, 2030 or 2034. Currently the most likely date was thought to be the CGPM in 2030. Of the mandatory criteria, the ones with the lowest achievement level currently were the validation of optical frequency standard accuracy budgets and the regular contributions of optical frequency standards to International Atomic Time (TAI). Dr Dimarcq highlighted the three options for redefinition. Option 1: A definition based on a single atomic reference transition – although at the current time there was no strong favourite transition identified. Option 2: A definition based on an ensemble of frequencies. Option 3: A definition based on fixing the numerical value of a fundamental constant. Option 3 was not feasible in the near future as no fundamental physical constant was known with sufficient accuracy. Dr Dimarcq concluded by stating that the CCTF planned to finalize their white paper on the redefinition of the second in 2022 and this would include the methodology for making the future choice of the new definition.

Dr R. Brown began the questioning by asking whether choosing Option 2 for the redefinition of the second might result in a definition that was continually changing over time and therefore not very well understood. Dr Dimarcq replied that there was a need to ensure that this was not the case and one of the conditions of the roadmap was the continuity condition with the previous definition of the second. Prof. Phillips stated his strong opposition with Option 2 and he likened this to previous times when the second was based on the mean solar day and the problems that this caused. He continued by stating that it was important to provide equal treatment to all the individual experiments on different atoms but that that did not mean that we should make a mistake in our metrology, concluding that it would be best to choose one atomic transition for the redefinition. He speculated that maybe after a period of time one of the many secondary representations may turn out to be better, or indeed it may turn out to be a nuclear transition that is better than them all and concluded by saying that if this was the case and

secondary realizations became better over a period of time the community would deal with it when it happened. Dr Dimarcq replied that it was indeed the intention of the CCTF to perform a full analysis of the implications of each of the options. Dr C. Salomon added that if fundamental constants were changing it would not be possible to determine this if an ensemble of transition frequencies was chosen for the redefinition of the second. Dr Dimarcq accepted this possibility and stated that it was one of the factors that the CCTF was considering. Prof. Phillips concurred that the ability of Option 2 to hide variations in fundamental constants was also a major concern of his. Dr E. Prieto agreed Option 2 could introduce dangerous dynamic changes for the other units that rely on the second. Prof. Ullrich concluded that the CCU had a strong interest in the work of the CCTF in this area. He added that he had recently refereed a Chinese proposal to place optical clocks on satellites, which was now going ahead, and this was very relevant for the CCTF and the CCU to monitor since it would be potentially very important for metrology and other scientific discovery.

Prof. Phillips concluded the discussion by raising that the current *mise en pratique* for the second involved the gravitational potential and the mean sea level, and asking that, as the polar ice caps melted and their mass is redistributed, what this meant for the definition of the second. On a more philosophical point Prof. Phillips asked what these definitions meant in the context of general relativity. Dr A. Steele suggested that the CCTF should prepare guidance for the extent by which the definition of the second could vary under Option 2 and how this, if at all, would affect the realization of the other units. This would be a major input in deciding between Option 1 and Option 2 in future.

4.2 Report on a possible redefinition of the candela

Dr M. Rastello presented on the key scientific questions in the definition of the candela. Dr Rastello introduced the reformulated definition introduced at the 26th meeting of the CGPM (2018) and explained that the defining constant K_{cd} makes a direct link between photometric and radiometric quantities for monochromatic radiation at 540 THz. It was reported that the present definition serves the practical requirements of global trade and industry very well, but there was still the scientific challenge that K_{cd} is not a fundamental constant but instead based on the response of the standard photopic observer as agreed by the CIE in 1924. This constant is now almost one century old and based on results of 272 observers from the UK, US and Japan. This has always been a difficult topic since photometry deals with visual quantities and yet the measurand is not directly accessible to the measuring instrument and may vary from one observer to another. Much more is now understood about the human eye than was known in 1924, especially the three families of cone cells in the eye whose response is wavelength dependent and how these responses are processed by the brain. It is foreseen that future methods of measurement may involve image-based radiometry and machine learning to link the physical scale directly to the perception of the individual observer. Because of scientific progress in the understanding of luminous perception using the cone fundamental system Dr Rastello explained that there could be future changes in photometric quantities. This cone-fundamental based photometric system would lead to a new link between photometry and radiometry. Dr Rastello concluded that this link and its characteristics are the key scientific challenges for any changes to the definition of the candela in the future.

Dr T. Bergen began the discussion by stating that this was indeed a very complex subject and that the current definition was based on very old data that was not representative of our modern understanding of vision. He stated that this proposed revision was the subject of ongoing work. Dr P. Blattner added that the CIE was working on this and had developed a roadmap for the subject. Dr Blatter added that the extent of any change would depend not only on science but also likely acceptance by industry, since any change would have an impact on measurement devices, manufacturers, regulation, and standardization. Prof. Ullrich added that this was an important and interesting development, but this would take time because of the requirement to engage fully with industry and other relevant stakeholders.

4.3 Report on the consensus value for the kilogram

Dr Stock presented on the dissemination of the consensus value for the kilogram. Dr Stock reminded the CCU that in 2017 the Consultative Committee for Mass and Related Quantities (CCM) concluded that the available measurements for the Planck and Avogadro constants did not pass the test for consistency and this would have resulted in inconsistencies that were unacceptably large. The solution was to use a consensus value (“an international mean kilogram”) for dissemination as determined from an ongoing comparison, until the dispersion in values became compatible with the individual realization uncertainties. It was decided that a Key Comparison should be organized every two years with the consensus value based on the average of the last three Key Comparison Reference Values (KCRVs). Because initially there were not three KCRVs to use, the first consensus value included data from the 2016 pilot study and the calibration campaign using the International Prototype of the Kilogram (IPK) in 2014 as well as the first Key Comparison. The consensus value is maintained by the BIPM using its Pt-Ir mass standards. The first Key Comparison was completed with four Kibble Balances, one Joule Balance, and two XRCD experiments. The KCRV was calculated as the weighted mean of the results with a standard uncertainty of 7.5 μg . The mass of the IPK, based on the first consensus value, was calculated to be 1 kg – 2 μg , with a standard uncertainty of 20 μg . This is the basis for world-wide coordinated mass dissemination for the coming years until the next consensus value. No adjustment to the international mass scale needed to be made but some NMIs’ uncertainties needed to be increased. Adjustments to the CMCs of NMIs were necessary to take into account the increased uncertainty in the consensus value relative to the previous uncertainty in the mass of the IPK, with respect to the Planck constant. Draft adjustments were calculated by an *ad hoc* task group of the CCM WG-M and circulated to the affected NMIs for approval. These were then updated in the KCDB. Dr Stock concluded by displaying the four dissemination phases for the kilogram. Dr Stock stated that the second Key Comparison has now been started.

Dr R. Brown asked what the criteria were for moving to the final stage of the plan and how long this would take. Dr Stock replied that four criteria for this had been specified by the CCM Task Group on the Phases for the Dissemination of the kilogram following redefinition. He added that it was not clear how long this process would take and there had been some estimates of ten years, although this had a large uncertainty associated with it.

5. COMMENTS ON WRITTEN REPORTS FROM OTHER ORGANIZATIONS AND INSTITUTIONS

Prof. Ullrich noted that in the CODATA report the committee announced that they would produce a statement on the impact of the redefinition of the second and that this would be very useful for the CCU and the CCTF. Prof. Ullrich also noted the memorandum of Understanding (MoU) signed between the BIPM and the IFCC and hoped that this would lead to increased engagement in future.

Dr R. Brown noted that from the CODATA report it was clear that G , the gravitational constant, remained a fundamental constant with one of the largest uncertainties associated with it and wondered whether there was current experimental work being undertaken to address this. Dr M. Newell reported

that the BIPM apparatus for measuring G was now being used at NIST and it was hoped that this would produce a value in time for the next CODATA readjustment.

6. **OUTCOME OF THE SURVEY AMONGST STAKEHOLDERS ON THE IMPLEMENTATION OF THE NEW DEFINITIONS OF THE SI**

Dr Stock reported on the outcome of the questionnaire sent to NMIs, liaison organizations and academic institutions on the implementation of the new definitions of the SI. Dr Stock reported that the CCU strategy working group had decided in January 2019 to perform this exercise, but that it had been delayed to 2021 because of the pandemic. The questionnaires had been finalized in early 2021 by the CCU President, CCU Executive Secretary and the BIPM Director. These were sent in March 2021 to NMIs of Member States, CCU liaison organizations and (via NMIs to) teaching organizations. The deadline for replies was the end of May 2021. There were replies from 17 NMIs, seven liaison organizations and from five schools, twelve universities and three NMIs replying on behalf of academic institutions that they had contact with. Dr Stock highlighted that it was difficult to summarize such a large volume of responses so the presentation picked out the key themes relevant to the CCU. No NMIs experienced difficulties in implementing the revised SI and there was evidence of a large quantity of events to promote the revision of the SI. NMIs also found that the information received from the BIPM, especially the SI Brand Book, was very useful. No significant effect on NMIs' customers was noted. The NMIs highlighted a large number of new opportunities they thought were opened up by the revised SI. In terms of liaison organizations the responses were in general similar to NMIs although some technical committees within the liaison organizations reported being affected by the revision, e.g. ISO/TC 12: Quantities and units, and the IEC felt the process was not fully transparent. In terms of teaching organizations there was in general no impact on the curriculum for schools but some universities, often those with close links to NMIs, had updated their course material. There was some suggestion that the new definition of the kilogram would be more difficult to teach.

Opening the discussion of the result, Prof. Ullrich noted that it was very gratifying that no major problems with implementation had been uncovered and concluded that this meant that the CIPM Task Group that had coordinated publicity surrounding the revision of the SI had done an excellent job. Prof. Ullrich observed that the questionnaire had produced many useful suggestions about future work that can take advantage of the revised SI. Dr R. Brown noted that despite the extensive efforts of NPL to communicate the changes in the UK there were still a couple of replies from universities who were not aware of the change. Dr R. Brown took this as an indication that it was still worthwhile to continue to deliver presentations on the SI revision to increase awareness and he confirmed that NPL intended to do this. Dr Stock remarked that in some cases the lack of awareness expressed may have been associated with the individual that the questionnaire was sent to and was not necessarily a reflection of the organization as a whole.

Prof. Phillips noted that one of the biggest changes, and main driver, for the SI revision had been the desire to bring electrical units back within the SI and wondered whether this had been remarked upon in the responses. Dr Stock said that no replies had been received to this effect. Mr P. Sebellin added that the change in electrical units had required the IEC to update many of its guidance documents but that this had presented no problems and they had been happy to do this. Dr Milton concluded the discussion by thanking Dr Stock for undertaking the huge quantity of work associated with the questionnaire, which had been initiated by Dr Stock's predecessor, and he reiterated how reassuring it was for the metrology community to receive these positive responses. Prof. Ullrich agreed that this had

been a very positive exercise and it gave the metrology community confidence that they had done their job well.

7. PROPOSALS FOR EXTENSION OF THE RANGE OF SI PREFIXES

Dr R. Brown presented on progress with the extension to the range of SI prefixes. He started off by showing the history of prefix coverage during the lifetime of the Metre Convention highlighting that we were already experiencing the longest period since 1875 without a change to the SI prefix coverage. Dr R. Brown then explained the drivers for extending the range of SI prefixes which included promoting usage in communities where the prefix range was not fit for purpose, progress in science requiring coverage of an expanded range of magnitude and, finally, ensuring that unofficial names did not become *de facto* adopted. Dr R. Brown then elaborated on the requirements of information technology where data storage will soon require prefixes for the non-SI units bit and byte in excess of 10^{24} , especially with the expected advent of quantum computing. Dr R. Brown noted that this was an area where the popular science media was active and there were already many suggestions in wide circulation for unofficial prefix names in excess of 10^{24} . Furthermore, he noted that Google's 'conversion calculator' already suggested that one hellabyte was equal to 1000 yottabytes. Dr R. Brown explained this was the background to the proposal to extend the range of SI prefixes using ronna for 10^{27} , quetta for 10^{30} and, symmetrically for sub-multiples, ronto for 10^{-27} and quecto for 10^{-30} .

7.1 Preparation of a resolution for the 27th meeting of the CGPM (2022)

Dr R. Brown reported on the CCU consultation that had taken place from March to November 2020 and that replies to this had been universally positive and were supportive of the proposals without change. Dr R. Brown reported that a draft CGPM resolution had been reviewed by the CIPM in June 2021 and feedback was received and acted upon: this had resulted in the updated draft CGPM resolution presented to the CCU now (CCU/2021-07). Dr R. Brown presented the roadmap for the extension to the range of SI prefixes and noted that at this stage the CCU's final approval of this draft resolution was being requested prior to final approval by the CIPM in October and presentation of the resolution at the 27th CGPM.

There were no comments on the paper as presented by Dr R. Brown and the draft CGPM resolution was unanimously approved by the CCU. Prof. Ullrich would take this matter back to the CIPM for final approval.

The first session of the meeting concluded at this point.

The second session began with a short address from Prof. C. Bordé, reminding participants of the work of the French Academy of Sciences and in particular its Academic Standing Committee for Science and Metrology, chaired jointly by Prof. Bordé and Prof. Salomon, who followed developments in the SI closely and with great interest.

8. REPORT ON THE WORKING GROUP ON CORE METROLOGICAL TERMS (WG-CMT)

Prof. Ullrich introduced the item by encouraging members to participate in an open discussion and encouraged consensus where possible, also recognizing that these needed to be acceptable solutions for the community at large. Prof. Neyezhnikov introduced the background to the working group, the membership and the terms of reference for the working group. The working group had come about because during the finalization of the 9th SI Brochure it became clear that there was a debate in the CCU about whether a unit was a quantity or a quantity value. This discussion then highlighted a wider issue for the CCU about the definition of core metrological terms, which was especially timely because the JCGM Working Group on the International Vocabulary of Metrology (JCGM-WG2:VIM) was drafting the VIM4. The CCU established the CCU WG-CMT to make a proposal to the CCU on definitions for ‘unit’, ‘quantity’ and ‘quantity value’. The working group met online three times in July 2020, November 2020 and June 2021 with off-line work in between meetings. Initial discussions led to no consensus with items of contention including: whether definitions referred to the abstract concept, or the concrete reality, of the terms; the meanings of ‘=’, ‘can be expressed as’, ‘is equal to’, etc; and the use of ‘magnitude’ in definitions and whether this could be properly translated into other languages. Participants drafted their favoured definitions in advance of the second meeting. The proposed definitions were edited, reducing these in complexity and length until there was majority agreement on the remaining text, with one opposing view. The CCU WG-CMT decided by majority not to include ‘magnitude’ in its definitions (with one opposing view). The VIM4 had also eliminated ‘magnitude’ on the basis it was implicit in ‘quantity’. The 3rd meeting aimed to build consensus for the definitions produced, noting that the VIM4 had already been released for consultation. The CCU WG-CMT then finalized their definitions by majority, with one opposing view from PTB. The CCU WG-CMT majority proposal for the definitions considered was:

Quantity

property of a phenomenon, body or substance that can be compared by ratio or by order to others of the same kind.

Unit

quantity adopted by convention as a reference.

Quantity value

expression of a quantity in terms of a reference.

NOTE 1: A quantity value is typically the product of a number and a unit or a position on an ordinal scale.

The alternative proposal from PTB was:

Quantity

magnitude of a property or a relation that can be measured or multitude that can be counted.

Unit

particular magnitude agreed on by convention.

NOTE: The unit of a magnitude is related to a quantity value with the numerical value one in a given system of units. The unit of a multitude is the number one.

Quantity value

numerical representation of a quantity in terms of its unit.

NOTE: When stating the value of a multitude, the counted entity must be specified.

(Specifying the entity could be done similar to the way it is done e.g. for the molar mass according to the SI brochure)

Prof. Neyezhnikov asked the CCU to consider this information and decide on the next steps. He proposed that one option would be communication of these proposed definitions (with the alternative proposal) to the CIPM for consideration and subsequently to the JCGM WG2. Prof. Neyezhnikov noted the aspiration of VIM4 for machine readable definitions but observed that, in future, definitions should also be made machine interpretable and machine actionable. This could be a possible future topic for the CCU WG-CMT or a similar group, but this would not be a task for the near future

Dr Krystek began the discussion by arguing that the stated conclusion in the CCU WG-CMT's final report that a unit is a quantity was not the consensus of the working group. Prof. Ullrich replied that the working group report stated that there was no consensus in the definitions agreed and Dr Krystek agreed to that point. Dr Krystek returned to his previous statement that the part of the final working group report stating that it was decided that a unit is a quantity was not fully agreed. Dr Stock replied that he has made this conclusion in the meeting because in the proposed PTB definitions it was stated that a quantity was the magnitude of a property and that a unit was a particular magnitude and Dr Stock therefore concluded that a unit was a quantity. Dr Stock said the same conclusion can clearly be drawn from the definitions agreed by majority. He then added that if this was not the case the proposed definitions from PTB were not complete. Dr Krystek stated that he did not agree with this interpretation and returned to the definition of quantity, arguing that first this had to be agreed on before it was possible to differentiate between quantity and quantity value. Dr Krystek proposed that according to the current VIM the defining constants of the SI were all quantity values and since all units had been derived from these by purely mathematical means then the units were also quantity values and so the SI Brochure was incorrect. Dr Krystek felt that there had not been sufficient compromise in the opinions of the working group when drafting these definitions.

Dr Prieto felt that Dr Krystek was not right to state that opinions were right or wrong, only that one was not in agreement with another, since these were difficult problems with no clear answers. Prof. Phillips expressed the opinion that this was not purely a scientific question, but instead one of definitions that must be chosen to be as clear as possible. The question of what is most clear will vary from one person to another and so definitive statements of right and wrong are not helpful – instead we must ask what solution leads to the greatest clarity. Prof. Phillips felt that using the term 'physical quantity' was more in line with people's perception of these terms, although he interpreted this as a quantity value (a pure number times a unit), which left the question how a quantity was different from this. Prof. Phillips concluded by asking the wider question about whether any mistakes were being made by stakeholders as a result of these definitions.

Prof. Ullrich replied that he thought it was necessary to consider a machine actionable version of these definitions and a machine would have difficulty with logical inconsistencies in the definitions. Dr D. Flater noted that the discussion thus far had been reopening the definitions discussed at the CCU WG-CMT. He suggested that a more important question that had not been addressed yet was the acceptance of the report of the working group as the final output of the working group, recognizing that there was a majority view with one dissenter. Prof. Ullrich replied that yes, the report was final, contained two different proposals, and that a consensus was not reached, and this would be reported to the CIPM for them to decide upon further action. At this point Dr Krystek agreed with Prof. Phillip's previous points that humans have no problems with these definitions but that machines may well do.

He reiterated the view that the definitions currently imply that the defining constants of the SI Brochure are quantity values because if the unit size was changed then the numerical value would change. Further he stated that it was necessary to first solve the definition of quantity since everything flows down from this. Dr Krystek did not agree with the statement that quantities could be compared by order since this did not relate to measurement. He mentioned that the only exception to this in his opinion was counting.

Dr R. Brown commented that he had liked the VIM4 concepts of general and specific quantity since this addressed many of the problems that arose from a confusion between consideration of an abstract quantity and the concrete example of a quantity.

Prof. R. Marquardt stated that there was no official IUPAC position on these terms but mentioned that opinions received from IUPAC members suggested that if either set the CCU WG-CMT definitions were accepted then it excluded pH from being a quantity because of its logarithmic nature. He added that he imagined a computer could be taught the final definitions decided upon, just as humans are taught these definitions. Dr Flater added that if machine interpretability is the eventual goal, then the approach so far had been wrong. Machine interpretation requires a coherent conceptual model in which each distinguished concept has a unique identifier, whereas terms in a lexicon simply have multiple senses that are distinguished based on context. CCU WG-CMT had been following in the footsteps of JCGM and ISO 704 in trying to do both at the same time, choosing terms from natural language as if building a lexicon but then limiting them to only one definition. This unnecessarily sets up a conflict over which sense of a term is canonical.

Returning to the output of the CCU WG-CMT Dr Louw stated that the report was clear that there was a majority opinion with one member not agreeing. He added that the CCU needed to note that point and move forward with the discussion from there. Prof. Salomon agreed with Prof. Phillips that the word quantity is vague, but that physical quantity sounds a lot more precise. Dr Karshenboim stated that he found the discussion difficult to understand because before agreement on definitions we have to have consensus on concepts, for instance whether a position vector is a quantity. He stated that these fundamental issues must be decided first before moving further. Dr Krystek stated his belief that reference to physical quantities was implicit in reference to quantities.

Following what had been a lengthy discussion, that had raised some new insights on these issues, but which had not produced significant movement towards consensus on any of the substantive issues, Prof. Phillips made some concluding remarks. He stated that it was clear that more work was required on these topics, highlighting machine readability and interpretation of definitions as a key future requirement. He added that there was still a lack of understanding of the concepts behind many of these important terms. Dr B. Güttler agreed and highlighted, referring back to the discussion about physical quantities, that the current VIM states “The concept ‘quantity’ may be generically divided into, e.g. ‘physical quantity’, ‘chemical quantity’, and ‘biological quantity’...” and he so was not sure that physical quantity covered everything we might consider a quantity. Prof. Neyezhnikov added his thanks to Dr Stock and Dr R. Brown who had helped with organization of the CCU WG-CMT and drew attention to the part in the WG report where it highlighted the proposed use of general and specific quantities in the draft VIM4. Dr Steele supported the agreement that had been achieved – namely that the topic needed more discussion – but asked about the timing of future work given that the draft VIM4 consultation had already been launched. Prof. Ullrich stated that the CCU WG-CMT had been an attempt to produce a BIPM position which would be fed into the JCGM. In the case where the BIPM has no clear consensus position on these terms Prof. Ullrich was unsure how this might affect the timings of the VIM4 process.

Concluding the agenda item Prof. Ullrich suggested that the CCU WG-CMT now turn its focus to the issue of machine readability of definitions, identifying other core metrological terms that would benefit from being considered by the group, and also beginning to consider quantities associated with counting following a proposal of a workshop from Dr R. Brown and Dr Güttler. Dr R. Brown added that there were many issues associated with counting in metrology, theoretically and practically, and a useful way to begin to address these would be via a joint CCU/CCQM workshop (since there was major interest

from chemistry and biology) with other CCs also invited (for instance Dr Rastello expressed interest from the Consultative Committee for Photometry and Radiometry (CCPR) and counting metrology is a major activity for the CCRI). The CCU agreed for Prof. Neyezhnikov, Dr R. Brown and Dr Güttler to lead the preparation of this workshop via the CCU WG-CMT. The CCU decided to continue the work of the CCU WG-CMT with the items discussed. Prof. Ullrich concluded by asking for other volunteers to join the CCU WG-CMT to help undertake its new work items.

9. REPORT ON THE REPLIES FROM MEMBERS AND LIAISONS ON THE CHOICE OF UNITS FOR ANGLES AND DIMENSIONLESS QUANTITIES

Dr Stock presented his summary of the CCU consultation on the units for angles and dimensionless quantities. It had been decided at the last CCU meeting, following a long discussion with no consensus, that all members and liaison organizations should submit their official organizational positions on these issues in time for this CCU meeting. Dr Stock reported that he had tried to summarize here the most salient part of the organizational replies, but that the full details were available in the individual responses, all available as working documents. In summary Dr Stock reported that for angle:

- PTB did not believe that there was any need to change the current status of angle in the SI Brochure, also explaining the way in which frequency and angular frequency were different physical quantities with the units, Hz and rad/s respectively.
- NPL thought there was value in updating the SI Brochure to acknowledge the confusion that can occur and explaining the importance of clearly stating the quantity being expressed and using explicit units where possible. NPL volunteered to make a proposal for revision of the SI Brochure.
- NIST recommended that the SI Brochure should treat angles as an independent quantity with the unit radian and the corresponding SI definition of the radian being 'The plane right angle is $\pi/2$ rad'. The designation of both rad/s and Hz being equal to 1/s would be abrogated.
- NMIJ felt that making radian a base unit would cause confusion that would greatly outweigh any possible benefits. In mathematics it was logically rigorous to treat angle as a dimensionless quantity with the unit one.
- INRIM stated that elevating the radian to a base unit would cause significant changes to dimensional analysis in mathematical and physical equations and this would have a negative impact on the scientific literature and create confusion.
- NIM proposed that a wide consultation was necessary before any decision was made to treat the unit of angle as a new base unit. NIM upheld the stance that the unit for angle should be changed from a derived unit to a supplementary unit.
- IUPAP were in favour of changing the SI designation of the unit radian for plane angle and phase angle from being a derived dimensionless unit to being an independent unit (six responses from members of IUPAP C2 had supported this position, with one clearly against and one with no clear opinion).
- IMU pointed out that no conceivable technological advance can lead to a need to refine the definition of the radian and stated that the radian cannot be a base unit in any system of units. IMU also stated that it is wrong to state $\text{rad} = \text{m/m}$.
- CIE reported that in practice no real problems are observed with the current status as students learn relationships between photometric or radiometric quantities directly. Most participants in the CIE found that the current treatment of angles in the SI Brochure is a pragmatic solution.

- CODATA reported that there was no consensus at the recent meeting of TGFC on the best way to deal with units for angles, but added that TGFC uses an explicit explanation of the units for quantities containing angle and frequencies for the CODATA 2018 recommended values.

In addition, three personal opinions were expressed from Prof. I. Mills (Honorary Member of the CCU), Dr Prieto (CEM, but expressing a personal opinion) and Dr P. Quincey (invited guest of the President). Prof. Mills stated that the many different units used for angle make it a mistake to imply or suggest that the unit of angle is always one, and he added that the SI Brochure should be updated to explain some of the confusions that can occur. Dr Prieto stated that before taking any revolutionary step such as the one taken with the latest revision of the SI, one must be very sure of its suitability, given the implications for the scientific and technical community. Dr Quincey recommended that the radian should become either a new base unit or some other special (non-derived) unit, with plane (and phase) angle having its own dimension.

In conclusion Dr Stock presented the opinions received alongside the various options that NPL had foreseen in their response. Including the response from OIML, provided during the following discussion, of the member and liaison organizations: six favoured the status quo (INRIM, NMIJ, PTB, CIE, IMU, OIML), one was in favour of editing the SI brochure for clarification (NPL), one was in favour of introducing supplementary units (NIM) and two were in favour of a introducing a new base unit and base dimension (NIST, IUPAP). CODATA reported no clear consensus.

Dr Stock added that several organizations had stated that to avoid ambiguity one should always use complete units for periodic phenomena, such as Hz or rad/s, rather than 1/s. He went on to point out that in fact this is already explicitly recommended in the 9th edition of the SI Brochure in Section 2.3.4 on derived units. Dr Stock finished his presentation by highlighting the replies received from members about other dimensionless quantities. NPL had stated that a full description of what is being expressed is essential, and the use of explicit units wherever possible is recommended. However, NPL also stated that where units are not possible the unit should be one, not the name of the identity being counted, although NPL fully expected standardized ‘counting units’ to be used downstream of the SI. NIST felt that counted quantities must comprise a positive integer and a specification of the entities being counted. In general, they felt that counts were not traceable to the SI because they involve characterizing what is being counted and therefore the task of defining most extended units will fall on the downstream users of the SI and not on the CCU. Finally, CIE felt that for dimensionless quantities the current treatment in the SI brochure provides clear and sufficient guidance and that quantities related to counting (e.g. number of photons) are considered just to be numbers.

Dr R. Lapuh apologized that he had not delivered an official position from the OIML but that from the comments received so far, he saw no problem in legal metrology for maintaining the status quo and stated that he would send an official letter to this effect in due course.

Dr R. Brown thanked Dr Stock for an excellent summary. He added that whilst the weight of opinion was for the status quo if those opinions were examined in detail there possibly was a consensus for editing the SI brochure for clarity, even if there was not support for adopting the radian as a base unit. Dr R. Brown added that many of the aspects associated with counting could be addressed at the proposed CCU/CCQM workshop. Dr Shirley supported the proposal to have another look at how angles are described within the SI Brochure perhaps via a separate committee. Dr Quincey, who had retired from NPL prior to the consultation to establish the organization position, delivered a statement on his views. He suggested that to make progress CCU needed to set aside the detailed arguments, and instead understand the root of the problem, which was best done by considering how the situation had developed: a historical accident entirely to do with presentation which, with some necessary small changes, could be solved. He also challenged the view that angles are a minority interest requiring superficial changes, proposing that it is the result of a significant error in the SI’s structure. He compared the position of angular quantities now to the position of electrical quantities 100 years ago

where there were arguments for 45 years and suggested the CCU not to spend a similar time discussing the topic, adding that it was especially important to get this right because of the move to the digital world.

Dr Holden stated that when he first heard about the issue he and colleagues at the IMU did not understand why this was a problem or the controversy. To mathematicians angular measures are mathematical constructs and dimensionless. He was of the opinion that introducing units unnecessarily would have unintended and unwelcome consequences.

Dr Mohr stated that he believed updates should be made to the SI brochure to clarify specific points to do with statements made about the hertz being equal to one per second in Table 4 and radians per second being equal to one per second in Table 6. More generally he made the point that it is often argued that treating angle as a base quantity in the SI would cause confusion, but he highlighted examples from the popular media (Wikipedia and Mathematica) which already routinely treated angles as base quantities without any confusion. Dr Clarke added that our most precise measurements are of frequency, which represented counting a number of cycles rather than measuring a varying number of radians and so he felt that both cycles per second and radians per second would be used for a long time to come and that the appropriate usage should be made very clear. Dr Krystek felt that Wikipedia was not a reliable source and mentioned that the German version of Wikipedia treated angle differently. He agreed with Dr Holden that angle was a mathematical concept and that it was not the property of measurement scientists. Dr T. Otto countered that Mathematica was a very good example of a machine readable and machine interpretable implementation of equations.

Dr Karshenboim stated he would prefer not to use the word cycle at all, since he believed that frequency is not only related to cyclic motion but to all periodic motion. Prof. Phillips mentioned that, unlike the earlier discussion about definitions, this was a case where confusion was caused and people were making mistakes, for instance literature was being published with errors of 2π because of confusion about the difference between Hz and rad/s. He suggested that a system is needed that minimizes the chance of errors, including when equations are being read by machine. Prof. Phillips also disagreed that angles were simply mathematical entities since they are regularly the subject of practical measurement and stated that the ongoing use of degrees proves that angles have dimension and are not purely mathematical in nature. Prof. Phillips continued, stating that the argument about angle in degrees being completely different from angle in radians is inconsistent with our usual metrology. He expounded that we do not say that a length in metres is completely different from a length in feet: they are both lengths, simply with a different choice of units. Prof. Phillips was in favour of modifications to the SI Brochure to ensure that the advice given in the text and the tables is consistent. Dr Marquardt mentioned that when teaching angles, it was necessary to use units to provide a full explanation of the concept. Dr Krystek replied that the use of degrees was historical, and this did not imply this came from mathematics. He reiterated his belief that an angle in mathematics was simply a geometric figure. He added that the sine function had a periodicity of 2π , that the arguments of such functions were always numbers and that the use of degrees with sine functions were meaningless. Dr Prieto commented that saying the unit of angular frequency is rad/s is incorrect, since this is the unit of angular velocity, although Table 6 of the SI Brochure applies this unit to both quantities. Dr Prieto continued that just as m/s is the unit of linear speed, which indicates the distance travelled per unit of time, rad/s indicates the angle travelled or rotated per unit of time and that frequency will appear later, when speaking of turns or revolutions per unit of time. Dr Steele noticed that this discussion – and especially the consideration of supplementary units – was also relevant to the wider debate about whether the distinction between base and derived SI units should be maintained in future.

The discussion concluded with no consensus on the preferred status of angle in the SI. Prof. Ullrich summarized the discussion stating that whilst the majority opinion still leaned towards the status quo, there seemed to be support for the SI Brochure being improved to prevent as far as possible misunderstanding and error associated with the use of angle. Prof. Ullrich raised the possibility of re-investigating the benefits of Supplementary units (a class of which the radian and steradian had been

members until 1995). Prof. Ullrich proposed a new CCU Task Group to examine this topic and suggested that Dr R. Brown should chair this group. This was agreed by the CCU and Dr R. Brown said that he would produce some draft terms of reference for the group to be discussed and agreed.

The second session of the meeting ended at this point.

The third session of the meeting began with Prof. Ullrich displaying the terms of reference for the proposed CCU Task Group on angle and dimensionless quantities in the SI Brochure (CCU TG-ADQSIB) that had been drafted overnight. The terms of reference were discussed and then agreed.

Regarding the proposal that membership of the Task Group was open to only one member from each member, observer and liaison organization, Dr Flater stated that the expert best prepared to speak on angles might not be the same person as the expert on the other quantities and that this constraint might be sub-optimal. Prof. Ullrich felt it was an important rule to keep this group from becoming too large. Dr Mohr commented that it would be difficult to have meetings in person because of the current travel restrictions due to the pandemic. Prof. Ullrich agreed that it was not essential to meet in person and that the main thing was that no members should be prevented from contributing. Dr Louw suggested editing the text to state that the group should meet at least once in person if possible, and this was agreed.

With item 9 on the agenda finished Prof. Ullrich presented a proposal for how the work of the CCU WG-CMT should develop. The next steps included:

- Organization of a CCU/CCQM workshop on the role of counts in the SI to be done by Dr Güttler, Dr R. Brown and Prof. Neyezhnikov. This would be open to all CCs, their members, liaisons and honorary members.
- Continuing its work along the lines of its existing ToRs, with a particular focus on the requirements concerning the machine readability and interpretability of the definitions.

The proposal for the second bullet point was to a) organize a CCU WG-CMT meeting inviting digitalization experts from the CIPM TG and EG on the Digital-SI and b) use the outputs of the CCU/CCQM workshop and the meeting in a) to refine the proposals for the terms 'quantity', 'quantity value' and 'unit'.

Dr Shirley asked whether as physical scientists there was enough expertise to lead properly this work on digitalization. Prof. Ullrich felt that including experts from the CIPM TG and EG on the Digital-SI would provide enough expertise. Prof. Phillips added that restricting the direction of the group to just the three terms listed was too limiting, especially given the discussion earlier on in the meeting. Prof. Ullrich agreed and stated that he wanted to expand this task in future and cited another part of the terms of reference which referred to identifying other core metrological terms that were of interest. Prof. Phillips was unsure whether such an exercise would lead to 'quantity', 'quantity value' and 'unit' still being important terms to define, adding that currently there was no distinction between physical and mathematical or abstract quantities. Dr E. Tiesinga, a member of the CCU WG-CMT, stated that he thought the working group had done their best with the definitions to date and was not sure extra effort would produce any additional benefit. Dr Prieto stated that considering physical quantities was very general and perhaps we needed to be more specific. Dr Prieto added that, as the work of the CCU WG-CMT had shown, reaching consensus is very difficult and that adding in other stakeholders would make this even more difficult.

Dr Steele mentioned that, in reference to the discussion yesterday on definitions, it was necessary to understand what consensus meant. He added that the proposed course of action to report the current state of affairs to the CIPM was sensible as this allowed the issues that caused deadlock in the working

group to be reported and analysed at a higher level. He said that this was important to resolve because the majority view of the working group actually aligned very closely with the proposal of the draft VIM4. Prof. Ullrich replied that it was important to consider the machine readability of the definitions and this had not yet been considered, but he agreed with raising issues with a lack of consensus to the CIPM for decision. Prof. Ullrich added that the definition of consensus was given in CIPM-D-01. Dr T. Quinn believed that so long as the language was clear then machines should be able to read it – the limitation was on the quality of the original English language. Prof. Ullrich replied that he was more concerned about the logic of the definition in terms of subsequent machine interpretability. Dr Karshenboim was concerned that some of these terms were already used in educational and legislative documents and that the working group needed to be careful that this was taken into account, as these were completely different communities using these terms in different ways. Dr Flater mentioned that the definitions that the working group produced could still be aligned with the SI Brochure with small changes.

Dr Flater returned to the issue of consensus, commenting that the CCU WG-CMT report had been quite clear that there was majority agreement with only one difference of opinion. He questioned whether what was being asked for was unanimity and not consensus. Prof. Ullrich stated that it was consensus that was requested, since consensus was not unanimity. Thus began a lengthy discussion about the interpretation of consensus within CIPM-D-01. Dr Mohr thought that the way consensus was being used in the CCU was closer to unanimity in that everyone had to agree. Dr Stock showed the text from CIPM-D-01 and stated that this was based on the text in the ISO/IEC Directive, in particular section 5.10: “The operation of the CC is by consensus amongst all present at the meeting which is understood to be: ‘General agreement, characterized by the absence of sustained opposition to substantial issues by any important part of the concerned interests and by a process that involves seeking to take into account the views of all parties concerned and to reconcile any conflicting arguments. Consensus need not imply unanimity’.” Dr Mohr continued that it was problematic to allow one disagreeing party to delay the process. Dr Tiesinga asked whether, in the case of a deadlock, there was a rule about how long the working group should continue in that state. Dr Milton intervened, stating that he did not believe that a time limit was specified, and added that in reflecting on consensus it was important to recognize that the intention of the CIPM had not been to allocate to members a veto vote, and so it was necessary to consider whether any sustained objections were enough to stop the progress of the work item considered. Dr Louw highlighted the part of CIPM-D-01 which stated that if no consensus is reached on a substantial issue, the CC President will refer the issue to the CIPM and report the differing views. His question for the CCU was whether the CCU wished to continue discussion of this issue, or whether the CCU wanted to send this to the CIPM for consideration. Prof. Ullrich stated that he would report to the next CIPM the current status of the definitions within the CCU WG-CMT as outlined in the report of the meeting and that he would also report to the CIPM that there was no consensus on how to proceed with the working group. The CIPM could then decide whether the working group continue to develop these definitions or stop their work at this point. Prof. Phillips mentioned that he now better understood the difference between consensus and unanimity, stating that consensus means that no one disagrees so strongly that they want to prevent the resolution from going forward. Unfortunately, he added, there is still not a clear line between unanimity and consensus. Referring to a point he previously made, Dr Karshenboim added that the meaning of words in different contexts is different and that CCU might need to consider this in our definitions. Prof. Ullrich stated that the aim was to concentrate on definitions for metrology. Returning again to the discussion of consensus, Dr Blattner stated that one of the working group meetings had been very fruitful in working toward consensus when the opposing opinion had not been represented and he doubted that there would be a fundamental change in these views in future, although it was possible to challenge these definitions with respect to counting and the requirements of digitalization. It was decided that Prof. Ullrich would communicate these views to the CIPM, and that one member was against proceeding with the continued development of these definitions within the CCU WG-CMT.

10. CCU STRATEGY FOR THE NEXT 10 YEARS

Dr Stock reviewed the CCU strategy and highlighted where he had made changes to update the document. This was mostly to update dates, add tasks that the CCU were currently undertaking and delete tasks that were completed. Generally, these were topics that had already been discussed in this meeting, i.e. SI prefixes, the questionnaire on the revised SI, discussion on core metrological terms, and the treatment of angles and dimensionless quantities in the SI. He highlighted that one task that had not been done, and would not be done, was the publication of the 9th edition of the SI Brochure in hard copy – it would be available online only. He highlighted that no progress has been made with discussion of the hierarchy of fundamental constants, which was perhaps a more theoretical consideration, whereas the SI was a practical measurement system. Dr Stock would circulate the updated document for comment.

10.1 CIPM Strategy and possible consequences for the CCU

Prof. Ullrich updated the CCU on the recent CIPM strategy, developed from February 2020 onwards in a series of mostly online discussions. Five key themes were identified:

1. Responding to evolving needs for metrology
2. Addressing key scientific challenges to advance to the global measurement system
3. Strategy for deepening engagement with other international organizations on measurement science issues
4. Reviewing the strategy for the future membership of the organization
5. Modernizing the operations of the organization.

Prof. Ullrich elaborated on these points highlighting that the work on evolving needs in metrology highlighted seven grand challenges (climate change and environment, health and life sciences, food safety, energy, advanced manufacturing, digital transformation and ‘new’ metrology) that would likely lead to two draft CGPM resolutions. One resolution would be on ‘emerging needs in metrology’ and one would be on ‘the global digital transformation and the International System of Units’. Prof. Ullrich also summarized the key scientific challenges highlighted by the CIPM strategy that might be relevant to the CCU: 1) The implementation of the revised SI, 2) Towards a possible future revision of the SI, 3) primary metrology outside the NMIs, and 4) The science of systems metrology.

Prof. Ullrich demonstrated how the CCU had already responded to the implementation of the revised SI through the CCU questionnaire. He also expected the CCU to be strongly involved in any future revision to the SI and to act as a coordinating body for the topics of primary metrology outside NMIs and the science of systems metrology.

Returning briefly between items to the membership of the proposed CCU TG-ADQSIB Dr Stock shared the current membership of those who had volunteered. Prof. Ullrich reminded participants that the membership should be limited to one per member, observer or liaison organization. Dr Shirley mentioned that the representatives from IUPAP and CODATA would be nominated in due course.

10.2 Update on the CIPM Task Group on the Digital SI Framework

Prof. Ullrich provided a vision of the future based on digitalization, smart cities, and sensor networks that the CIPM Task Group on the Digital SI were considering. Prof. Ullrich put this in the context of the quality infrastructure where not only was metrology important but also accreditation and standardization. He made the point that these processes, nationally and internationally, needed to be fully digitalized and that widespread agreement was required on how to do this. Prof. Ullrich stated that this was covered by the CIPM's 'Grand Vision' document. Indeed, the CIPM Task Group on the Digital SI had started some of this work and has appointed an expert group to provide recommendations on uniform digital data exchange formats. The mission of the CIPM Task Group was to provide a world-wide agreed, uniform, unambiguous, authoritative and dependable data exchange framework based on the SI, coordinate this effort with all stakeholders, and provide suggestions to make the SI Brochure machine readable.

The long-term aim of the CIPM Task Group was to establish a framework that meets FAIR principles (respecting business and privacy constraints) and allows all aspects of the international measurement system – measurement results, uncertainties, traceability and provenance – to be accessed and interpreted digitally, enabling machine to machine communication and analysis. Prof. Ullrich then provided an example of the application of this to a mass calibration traceability chain and how important all the component parts of these were. The plan was to have agreement on the representations for all such core data and metadata. Prof. Ullrich stated that CODATA and the European Open Science Cloud had already expressed interest in involvement in this process. Prof. Ullrich explained how this related to the three levels of the SI Digital Framework: the SI core, the service layer and then the application layer. Prof. Ullrich stated that this was a long-term effort but that shorter term goals would cover metadata models for quantities and SI units, digital representation of key reference documents (such as the SI Brochure, GUM and VIM) and improving on-line access to data in the KCDB and Joint Committee for Traceability in Laboratory Medicine (JCTLM) database. Longer term aims included digital representations of measurement procedures and key comparison data. Prof. Ullrich reported that much of this had been discussed at The International System of Units in FAIR digital data conference that had taken place in February 2021 (<https://www.bipm.org/en/bipm-workshops/digital-si>). Prof. Ullrich envisaged the role of the CIPM as an anchor of trust in this process particularly, for instance, in the assurance of digital calibration certificates. Prof. Ullrich concluded by explaining that in response to the two draft CGPM resolutions on evolving needs in metrology and on the digital SI framework he foresaw the establishment of a multidisciplinary forum on 'Metrology and Digitalization' with other international organizations.

Opening the discussion on the presentation Dr Quincey stated that when the SI is built into software the principles of quantity calculus become essential and yet from what was said previously, many of the proposals for the treatment of angle would not be a good basis for software. He believed the CCU needed to be clear that unless a significant change to the treatment of angular quantities is made, software for the SI will inevitably be unsatisfactory. Dr Tiesinga was concerned that there was overlap between the CCU WG-CMT and the CIPM Task Group on the Digital SI, and was worried that the CCU WG-CMT was too late coming to this task. Prof. Ullrich did not think this was the case but encouraged the two groups to work together, perhaps with the joint meeting previously suggested as a route to starting this. Prof. Ullrich highlighted that the main requirement was to work at pace because the world outside metrology was already making fast progress with this topic. Dr Shirley thought that this was an enormous task, much larger than just metrology and that many other organizations were already involved. Dr Shirley was worried that the CCU and CIPM was moving forward too quickly without integration with other organizations. Prof. Ullrich thought it was necessary to work quickly to catch up with the work going on outside metrology and provide the view of metrology into this discussion. Dr Newell stated that it was not just angle that caused problems for the digital world and the FAIR community, and that difficulties existed in many other areas such as newton metre for torque,

which is dimensionally equivalent to energy. He added that many of these problems occurred in the derived units section of the SI Brochure – humans understand the differences but machines would not. Dr Flater quoted Maxwell that ‘a unit is of the same kind as the quantity being expressed’. He continued that this idea has been lost because we have single units being used for different kinds of quantity and this was the biggest problem for digitalization because it is difficult to communicate the context in which the units is being used. He noted that the greatest of these problems was for the unit one: everything that does not have an established dimension within the SI is expressed with the unit one and so these quantities are potentially all interchangeable unless some additional constraints are imposed. Dr Flater noted that he and Dr R. Brown were in agreement that counting units will be defined downstream of the SI Brochure but Dr Flater thought that section 5.4.7 of the SI Brochure needed update to allow this to happen.

In light of the discussion Prof. Ullrich asked whether anyone wanted to change their opinion about the future direction of the CCU WG-CMT. Dr Tiesinga stated that he was still concerned that nothing new could be added by further discussion. Dr Flater wanted to separate the terminology debate from the digitalization agenda, but Prof. Ullrich replied that he did not think this was possible because people were already working on digital calibration certificates outside the metrology community. He raised the need to address counting which was increasingly relevant in the new SI. Prof. Phillips concluded the discussion by expressing his optimism, from the IUPAP point of view, that the CCU WG-CMT would be able to produce something that was useful for the digital community. He added that in the digital world machines needed help to understand situations where the same unit was used for different quantities.

10.3 Other possible future themes: systems metrology

Prof. Ullrich highlighted that systems metrology could be a future theme for the CCU and that PTB had been working on this topic for over a year now. This relates to networks of sensors and how one might organize and calibrate these to achieve proper traceability. He added that it was also relevant to smart cities and personalized medicine. In response Dr R. Brown highlighted that performing foresighting exercises to examine future technologies was very useful. He mentioned the metrology foresighting document that NPL had recently produced that was freely available and may provide some useful guidance as to future topics for the CCU: <https://doi.org/10.47120/npl.8948>.

11. REVIEW OF MEMBERSHIP

11.1 Requests for membership or observership of CCU

Prof. Ullrich reported that there had been a membership application from National Scientific Centre ‘Institute of Metrology’ (NSC-IM) in Kharkov, Ukraine. To introduce the application Prof. Neyezhnikov gave a presentation about the institute, which had celebrated its 120th anniversary this year, and provided highlights of its scientific contributions over the years, including the measurement of fundamental constants such as the proton gyromagnetic ratio. Prof. Neyezhnikov highlighted the current role of the institute in providing underpinning metrology for society and the economy, as well as maintaining national standards and participating in consultative committees at the

BIPM. Prof. Neyezhnikov concluded by highlighting the role NSC-IM had played in promoting the SI within the Ukraine and more widely.

Responding to the application, Prof. Ullrich reminded participants of the requirements for membership in CIPM-D-01. As there were no objections the CCU agreed to recommend to the CIPM that NSC-IM become members of the CCU.

11.2 Review of membership of CCU working groups

Prof. Ullrich and Dr Stock reminded the CCU that eligible members wishing to join or leave any of the CCU's working groups or task groups should contact Dr Stock directly.

12. ANY OTHER BUSINESS

No other business was raised.

13. DATE OF THE NEXT CCU MEETING

Prof. Ullrich stated that since this meeting had been online it would have been useful to have an in-person meeting in 2022. However, given the busy meeting calendar of the BIPM in 2022 and the likelihood of substantial progress not being made on the topics discussed in only one year, the plan was to have the next CCU meeting not earlier than in two years' time. Prof. Ullrich suggested that the exact timing of the CCU meeting would be agreed in due course by the CCU Strategy Working Group depending on progress with the topics under consideration by the CCU, its working groups and task group.

Prof. Ullrich added that this was likely to be his last CCU meeting as CCU President and he stated that it had been his privilege to chair the CCU at a most exciting time for metrology, particularly during the revision of the SI. Prof. Ullrich warmly thanked the CCU for their hard work over his time as CCU President.

In the absence of further business, the meeting closed at 14:00 UTC.

Dr R. J. C. Brown
Rapporteur, 27 September 2021

14. DECISIONS AND ACTIONS FROM THE 25TH MEETING OF THE CCU

Actions

- A1. Prof. Ullrich to present Draft Resolution C of the 27th Meeting of the CGPM (2022) ‘On the extension of the range of SI prefixes’(CCU/2021-07) to the CIPM in October 2021 for final approval.
- A2. Prof. Neyezhnikov, Dr Güttler and Dr R. Brown to organize a joint CCU/CCQM workshop on quantities that are counted as a new task within CCU WG-CMT.
- A3. Prof. Ullrich to communicate to the CIPM the final report of the CCU WG-CMT on ‘unit’, ‘quantity’ and ‘quantity value’ explaining that a majority opinion was reached but with one member disagreeing.
- A4. Prof. Ullrich will communicate to the CIPM that one member was not in favour of the CCU WG-CMT continuing its discussion on ‘unit’, ‘quantity’ and ‘quantity value’ as part of its updated remit.
- A5. Dr Stock to circulate the updated CCU strategy document to all members for comment.
- A6. Eligible CCU members, observers and liaison organizations wanting to join or leave the CCU’s Working Groups and Task Group should contact Dr Stock.
- A7. Prof. Ullrich to present to the CIPM the recommendation that NSC-IM, Ukraine, become members of the CCU.

Decisions

- D1. Draft Resolution C of the 27th Meeting of the CGPM (2022) ‘On the extension of the range of SI prefixes’ (CCU/2021-07) was unanimously approved by the CCU without change and sent to the CIPM.
- D2. The final report of the CCU WG-CMT on ‘unit’, ‘quantity’ and ‘quantity value’ was accepted by the CCU.
- D3. The CCU WG-CMT will continue its work according to its terms of reference and the items discussed in the meeting.
- D4. The CCU decided to form a new Task Group on angle and dimensionless quantities in the SI Brochure (CCU TG-ADQSIB) chaired by Dr R. Brown.
- D5. The CCU agreed to the draft Terms of Reference of the CCU TG-ADQSIB.
- D6. The CCU decided to recommend to the CIPM that NSC-IM, Ukraine, become a member of the CCU.