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International development of the SI in FAIR digital data

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ABSTRACT

The International Committee for Weights and Measures has recognised the need to provide support for digital representations of the International System of Units (SI) and related metrological concepts, such as traceability and measurement uncertainty. A specialised Task Group was established to address this in 2019. This summary reports on the activities of the task group to date, which include an overarching "Grand Vision" document, sketching out an SI Digital Framework, and an international online workshop, "The SI in FAIR digital data", held in February 2021, to engage a wide audience in discussions about a solution.

1. Introduction

The world has adopted the International System of Units (SI) as a common system of measurement [1]. Under the oversight of the International Bureau of Weights and Measures (BIPM), supported by an international mutual recognition arrangement among nations [2], SI units are realised by national metrology institutes (NMIs) and disseminated through national and international networks known as quality infrastructures. The term 'infrastructure' here is apt because these processes occur almost imperceptibly, yet modern society could not function without trustworthy measurements from this system. In 2019, the redefinition of SI units–the outcome of years of effort and cooperation between many specialist groups–went so smoothly that few would have noticed were it not for the associated publicity. The German Chancellor acknowledged this extraordinary feat of international cooperation in her address to the World Economic Forum that year [3]. The Chancellor also recognised the challenges posed by new disruptive digital technologies, which are leading to a fourth industrial revolution. In this context, there is more work to be done on the SI: digital representations of physical quantities and measurement data are urgently needed to support the digital transformation of national and international quality infrastructures.

The SI redefinitions adopted in 2019 did not address the representation of SI units. While the SI Brochure describes the preferred formatting of SI units in printed form, it does not extend to digital representations [4]. Moreover, representations of the concept of metrological traceability, which is vital to the trustworthiness of critical measurement systems in society, have never been formalised. Other important metrology references, like the *Guide to the Expression of Uncertainty in Measurement* (GUM) and the *International vocabulary of metrology – Basic and general concepts* (VIM), are yet to consider the requirements of digital systems [5,6].

The International Committee for Weights and Measures (CIPM), which directs metrological activities carried out by parties to the Metre Convention, has recognised the need to enhance support for the SI in a digital world and has established a Task Group on the "Digital SI" (108th meeting of the CIPM, Decision CIPM/108–28, Oct 2019). The primary mission of this group is:

- To develop and establish an agreed world-wide, uniform, unambiguous, authoritative, and dependable data exchange framework based on the SI described in the current SI Brochure.
- To propose suitable actions towards making the SI Brochure machine readable.
- To coordinate this effort with all relevant stakeholders by exploring and/or establishing suitable liaisons.

To support the CIPM Task Group, an international team of experts in digitalization related to metrology was assembled in November 2019 (the authors are current members of this expert group).

In this summary paper, we report on the activities and plans of the CIPM Task Group. Section 2 describes an initial overview of the task, called the "Grand Vision", then section 3 describes the main outcomes of an international workshop held online in February 2021. In section 4 we briefly discuss CIPM plans for future collaborative activities and in section 5 we draw conclusions.

2. A Grand Vision guided by FAIR principles

As a first step, the task group has prepared a "Grand Vision" document that sketches out a framework for digital transformation of the SI, called the SI Digital Framework [7]. This document emphasizes the importance of FAIR principles (Findable, Accessible, Interoperable, and Reusable data and services) because they can significantly enhance the potential for reuse of data by digital systems [8]. FAIR-principles-based metadata, such as the kind of quantity, measurement accuracy, provenance of errors, etc, will facilitate the use of computer reasoning, machine learning (ML), and artificial intelligence (AI) methods. In the context of increasingly interconnected and automated environments, such as the Internet of Things (IoT) and cyber-physical systems, metadata can be used to ensure that physical quantity data generated by sensors is correctly interpreted for data analysis. In the context of

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scientific research, FAIR metadata underpins the need for independent researchers to re-examine and replicate research findings and for digital systems to extract knowledge automatically from large and diverse sources of research data.

The framework is intended to do more than just represent units of measurement in digital form. It will support a description of the system being measured and how measurements were made, as well as the workflows associated with the final measurement results obtained (data, models, and software). The framework should raise the level of machine readability, from basic capabilities to a full machine-actionable knowledge representation. Machine-actionable information will allow automatic assessment of the provenance, metrological traceability and fitness-for-purpose of datasets and enable use of ML and AI tools.

In the near term, a SI Digital Framework will cover:

- Interoperable data and metadata models for quantities and SI units;
- Digital representation of (the knowledge in) key metrological documents: the SI Brochure, the VIM, and the GUM;
- Establishment of open, high-quality, access to data, services, and tools, that are of verified quality, such as the Key Comparison Database (KCDB) and the Joint Committee for Traceability in Laboratory Medicine (JCTLM) database [9]; and
- Adoption of digital calibration certificates to support metrological traceability in digital systems.

In the longer term, the SI Digital Framework will address:

- The digital representation of measurement procedures, measurement workflows, analysis methods, provenance, and traceability chains. This will allow machines to access and act upon information with little or no human intervention.
- Digital representation of data related to measurement key comparisons and other types of measurement comparison.
- Embedding a digital framework to establish traceability at the points of measurement in various types of cyber-physical systems, such as smart sensor networks, IoT environments, and autonomous systems.

Fig. 1 shows a schematic view of the SI Digital Framework, which consists of three layers:

1. An SI core representation, approved by the CIPM, with metadata models and exchange format implementations for basic quantity data elements, comprising values, units, and uncertainties.
2. A services layer, implemented by NMIs, the BIPM and related organisations, with open data formats and software tools and services that build upon the SI core representation. Such services will improve data quality and transparency; they will support assessment that data is fit for purpose, facilitate life-cycle analysis, and enable data to be prepared for analysis.
3. An applications layer, developed and deployed in the broader metrology community and in research disciplines that rely upon the SI. This layer will consist of tools and services for domain-specific applications, including sophisticated analysis and AI/ML methods. By building on the SI core and services layers, applications will benefit from metrological traceability and hence be able to achieve high levels of reliability.

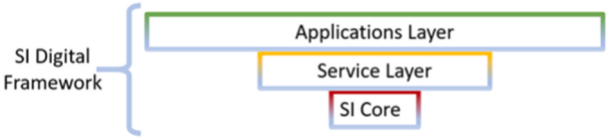

Fig. 1. The SI Digital Framework consists of three layers.

3. The SI In FAIR digital data

An international online workshop was organised by the expert group and the BIPM, and held from February 22nd to 26th, 2021. The workshop was intended to provide an opportunity to hear about the CIPM vision and to encourage discussion about the next steps to be taken. All regional metrology organisations (RMOs) contributed a summary of activities in their regions to the meeting and many international science, engineering and metrology organisations also presented to the workshop, including: the International Laboratory Accreditation Cooperation (ILAC), the International Organization for Standardization (ISO), the International Organization of Legal Metrology (OIML), the International Electrotechnical Commission (IEC), the Committee on Data for Science and Technology (CODATA) and the GO FAIR initiative. There were also contributions from corporations, including Siemens, Mitutoyo, and Wolfram. The workshop was very well attended, with over six hundred people joining the opening session and similar attendances at other sessions.

The workshop programme was designed to facilitate participation from around the world, with sessions repeated in different time zones on days 2, 3 and 4. On day 4, opportunities for wide-ranging discussion were provided in the form of parallel break-out sessions, in which panels of experts led discussions and responded to comments from attendees online. Four main themes were addressed in these sessions: the SI core representation and services, interoperability; machine-actionable metadata and data, FAIRness of data; digital calibration certificates; readiness of data for AI/ML. Recordings of all sessions have been made available by the BIPM [10].

A great deal of information was shared at this workshop. A few of the points identified were:

- A SI Digital Framework provides fundamental parts for an overarching digitalization in the international quality infrastructure. Leading organisations from industrial metrology, legal metrology, accreditation, standardization and scientific unions are challenged to find a common language in the digital transformation. It was emphasized that CIPM could be the trustworthy anchor for the coordination of the transformation of the SI into a digital world.
- The development of digital formats for calibration certificates (DCCs) will be a useful focal point for further collaborative work. The DCC must incorporate suitable formats for many different core elements, including physical quantities and units, quantity values, uncertainties, sources of common measurement errors and hence correlations. DCCs will also need to make use of persistent unique identifiers for digital objects and there will be a need for satisfactory processes to validate, authorise (endorse and sign), and revoke (withdraw) a DCC.
- There are already services available that support digital representations of units and physical quantities (controlled vocabularies, taxonomies, ontologies, etc, see Refs. [11–13]). Some scientific communities have invested considerable effort in developing and applying these tools. However, there are unresolved problems and gaps remaining with no common view of the underlying concepts. Effort should be made to engage with this work in the SI framework instead of developing new formats. However, the CIPM needs to address the fundamental requirements for complete expression of physical quantities. Fundamental concepts should be identified in the SI framework and should guide adoption and, where necessary, adaptation of existing services.
- A digital framework for the SI should address interoperability with customary units. While the underlying internationally agreed physical measurement system is based on the SI, as explained in the Introduction, other customary units are also used today when reporting quantities. A digital framework could facilitate the unambiguous use of customary units, by providing a clear and

metrologically traceable relation to the underlying SI, e.g., through recognised conversion factors.

- Correct representation of measurement uncertainties will be critical to achieving proper metrological traceability and interoperability. This requirement goes beyond the usual demands on FAIR data and suggests that an extension of principles for FAIR-and-metrological-traceable data may be needed.

3.1. Use-cases

A call went out, at the same time as the online workshop was announced, asking for the submission of use-cases that describe situations where unambiguous machine-readable representations of data and units of measure are important. Fourteen submissions were received, some of which also drew attention to the importance of machine-readable representation of metrological traceability.

These use-cases will now be used to help assess the requirements for a digital framework and to demonstrate how a digital framework can be applied in specific scenarios.

4. Discussion

The CIPM Task Group expects development of the digital framework to involve a wide range of activities. Beneath existing stakeholder networks, the SI Digital Framework will benefit from NMIs, the RMOs and the CIPM/BIPM engaging with communities from science and experts on FAIR data. This would involve active participation and collaboration at the national, regional, and international levels, such as the European Association of National Metrology Institutes (EURAMET) and the European Open Science Cloud [14], the Research Data Alliance (RDA) [15], CODATA [16], GO FAIR [17], the Allotrope Foundation [18], and the ISC World Data System [19].

NMIs and the CIPM/BIPM are encouraged to establish mechanisms and incentives for long-term support, investment, and continuous development of the SI Digital Framework data, services and tools in the NMIs, the BIPM, and international data quality infrastructure, with formally established data stewardship roles, responsibilities and activities.

Digital transformation of something as fundamental as our system of measurement and associated measurement and quality infrastructures will inevitably present opportunities for innovation. We should not blindly translate current practices, or we will miss new opportunities presented by digital technology. Nor would such a strategy be satisfactory to achieve fully machine-actionable formats for data, because we must recognise the importance of tacit knowledge that skilled people use to interpret data and find a way to encode that too. Mechanisms need to be put in place to support sustainable outcomes. Domains such as industrial metrology consider a life-time of interfaces, software and formats of 30 years and more. However, such opportunities will introduce some tension into the development of the framework. On one hand, there is a desire for a digital quantity and unit of measurement framework to support the emerging technologies of the fourth industrial revolution, like Industry 4.0. This is an immediate and pressing need. On the other hand, digital transformation, with its huge capacity for data processing, offers opportunities for completely new applications, powered by technologies like AI and ML, as well as rigorous realisations of fundamental metrological principles like metrological traceability. Such applications will take longer to emerge, but we must anticipate their arrival and build an infrastructure to support them. Specialist knowledge of metrological principles held essentially in NMIs and knowledge from FAIR data experts must be mobilised to ensure that solid foundations are put in place for the SI Digital Framework. This must be done from the outset to ensure that a robust and reliable infrastructure is constructed, which will be fit for purpose long into the future.

5. Conclusions

Having carried out the redefinition of SI units in terms of constants of nature in 2019, the CIPM has now turned its attention to the digital world and recognises the importance of extending support for representation of quantities, units, and other fundamental metrological concepts, to digital formats. This task is considerably more complicated than might at first be imagined. However, at the end of the 2021 BIPM Workshop, the OIML and CODATA signalled their intention to cooperate and collaborate with the CIPM in this endeavour and an invitation was extended to all scientific and metrological organisations to join in this important effort. Indeed, there is rapidly a growing research community working on these problems. Many submissions to the IMEKO World Congress this year are related to digital issues and there is a new IMEKO technical committee (TC6), which is primarily focused on digital transformation in metrology.

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