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Editorial

Editorial for Special Issue "Metrological Traceability"

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Metrology, standardisation, accreditation and conformity assessment are pillars of the *quality infrastructure*, an extensive network of organisations that, working together, deliver reliable measurements throughout modern society. Whenever important decisions are based on information obtained by empirical measurement, the quality infrastructure can be called upon to ensure that measurement results are accurate and important.

Metrological principles ensure that measurement results are scientifically meaningful. That is, measurands are characterised with respect to metrological references to ensure that measurement results can be compared. The critical importance of comparability is highlighted in a joint declaration by the BIPM, OIML, ILAC, and ISO, asserting that the consistency and comparability of measurement results are necessary to achieve the missions of those organisations [1].

Metrology is unusual among scientific disciplines in that it does not have a widely recognised curriculum describing its core concepts and principles. It does not have the kind of canonical textbook tradition found in established academic fields, such as classical mechanics or chemical thermodynamics. Several normative documents are maintained by the metrology community: the SI Brochure [2], the Guide to the Expression of Uncertainty in Measurement [3], and the International Vocabulary of Metrology [4]; however, these are reference documents for practitioners. They serve primarily to standardise terminology and notation rather than to convey foundational understanding.

The practice of metrology has distinctive characteristics compared to other scientific disciplines. NMI metrologists usually develop a high level of expertise in a particular field, although they often enter an NMI with no prior experience in metrology. Metrological knowledge is primarily acquired through interpersonal interaction over extended periods: experienced metrologists guide newcomers in the specific aspects of a field. Importantly, knowledge acquired through shared practice creates a pragmatic context for the preservation and transmission of knowledge. This is a hallmark of *communities of practice* [5]. Such practice-based knowledge contrasts with that acquired through a well-defined theoretical curriculum.

The metrology community recently initiated a digital transformation. This transformation will eventually have consequences for all stakeholders in the quality infrastructure, so an inter-disciplinary forum has been established to advise the CIPM on the implications of the digital transformation for the quality infrastructure [6]. One of the most significant challenges posed by this transformation will be to achieve *semantic interoperability* when information is exchanged between digital systems. That is, when data is exchanged between autonomous digital systems the meaning associated with metrological information must be preserved.

The digital transformation in metrology exposes the tacit forms of knowledge held by metrologists in tight-knit communities of practice. Digital systems cannot operate on tacit knowledge—they require explicit, formal representations. Consequently, the elicitation and formalisation of metrologists' knowledge are prerequisites for progress

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in the digital transformation. This Special Issue explores one important example of this: metrological traceability.

The Forum-MD, in association with IMEKO, held a joint workshop on metrological traceability during the 2024 IMEKO World Congress [7]. The workshop brought together eight metrology experts to discuss metrological traceability in the context of the ongoing digital transformation of metrology. It was divided into two sessions: *Session 1: From Foundational Principles to Digital Traceability* and *Session 2: Traceability for Emerging Measurement Technologies*. Recordings of the workshop are available online: individual presentations and abstracts are available in [8], while archival recordings of the two sessions are available in [9,10].

The present Special Issue, titled "Metrological Traceability", consists of five papers contributed by speakers at the 2024 workshop. These papers further develop topics discussed during the workshop. They may be read in a loose conceptual arc extending from practical implementations towards more conceptual frameworks, as follows.

In "Metrology for Virtual Measuring Instruments Illustrated by Three Applications", Schmelter et al. address traceability and uncertainty in virtual measurement systems, showing how simulation and virtual instruments can be integrated into the measurement process through three applications: a virtual coordinate measuring machine, a tilted-wave interferometer, and a virtual flow meter. They highlight the need for traceability and rigorous uncertainty evaluation in virtual metrology techniques.

In "Traceability in Data Spaces: From Individual Measurements to a Digital Product Passport", Eichstädt and Niederhausen discuss digital traceability in shared data spaces. They explore methods for validating metadata and data quality in digital data ecosystems, and examine the concept of Digital Product Passports as a means of embedding SI-traceable measurements within these digital environments as part of a broader digital quality infrastructure.

In "VNA Tools—A Metrology Software Supporting the Digital Traceability Chain", Zeier et al. introduce a software suite called VNA Tools built on a computational engine that enables modelling and uncertainty evaluation in vector network analyser measurements. The authors emphasise the importance of propagating detailed information required for uncertainty evaluation and demonstrate that doing so supports metrological traceability along complex calibration chains.

In "Provenance in the Context of Metrological Traceability", White shows that existing provenance data models, particularly W3C's PROV, can be used to describe measurements and related metrological data. The paper argues that documenting how data and results are produced can improve quality, reliability, and interoperability when communicating measurement data. It demonstrates how provenance information can provide context for traceability chains and help formalise traceability metadata in cross-domain applications.

In "Modelling Metrological Traceability", Hall explores a structured modelling approach to traceability chains. The paper focuses on representing residual measurement errors as physical quantities in measurement models, and propagating their effects through model sequences representing traceability chains. It emphasises a formal framework, including the use of a semantic modelling architecture (inspired by model-driven engineering), to support rigorous and semantically consistent representations of traceability.

These papers illustrate ways in which the metrology community is adapting to digital transformation. Collectively, they suggest that traceability should be understood not merely as a documented chain of calibrations with stated uncertainties, but as a semantic construct required to preserve meaning when measurement results are shared across the quality infrastructure. Knowledge held tacitly in expert communities can now increasingly

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be codified into formal, machine-actionable representations that support interoperability across digital systems.

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Abbreviations

The following abbreviations are used in this manuscript:

BIPM	International Bureau of Weights and Measures
OIML	International Organisation for Legal Metrology
ILAC	International Laboratory Accreditation Cooperation
ISO	International Organization for Standardization
NMI	National Metrology Institute
CIPM	International Committee for Weights and Measures
Forum-MD	CIPM Forum on Metrology and Digitalization

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