The international dimension of digitalization in metrology

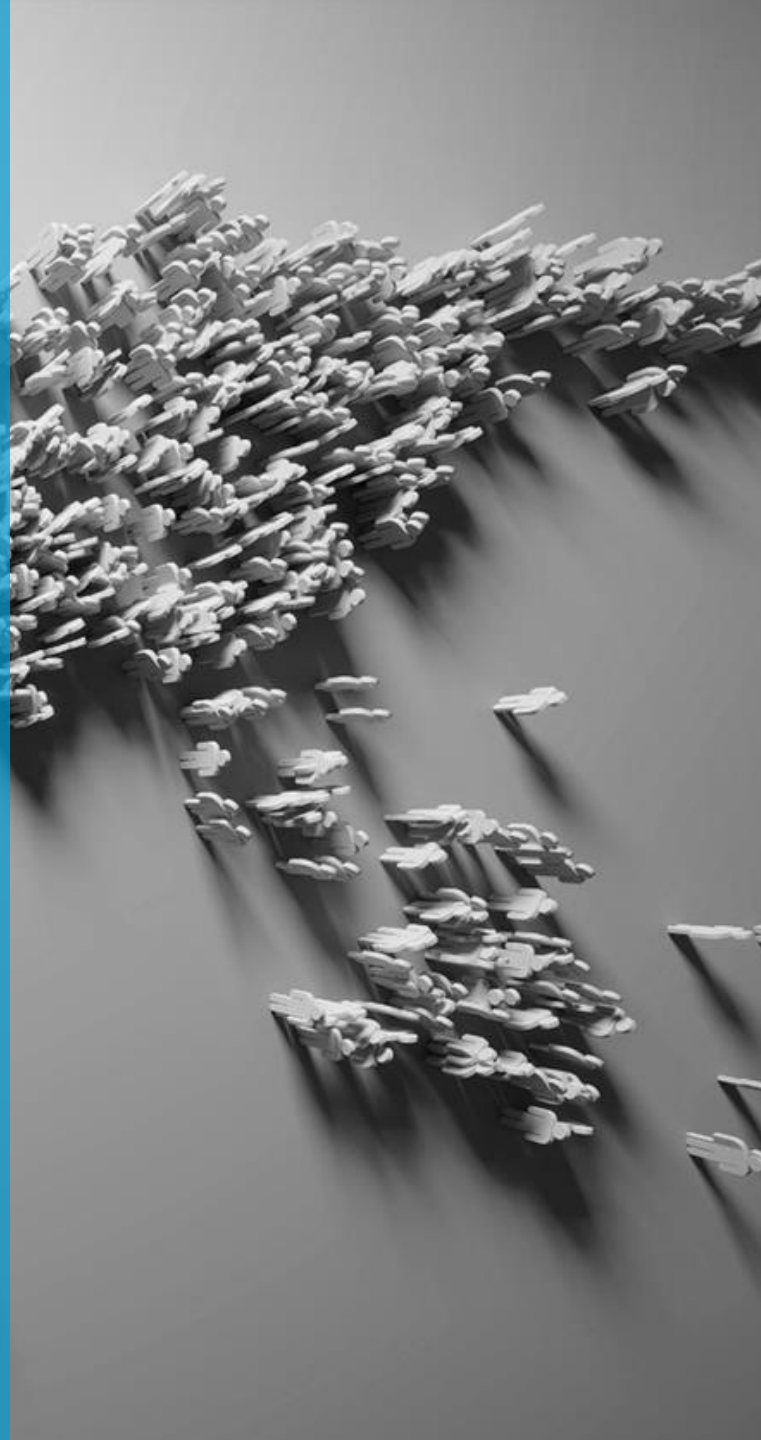
Highlights, challenges & strategies of metrology from today to digital tomorrow

Prof. Dr. Cornelia Denz
Physikalisch-Technische Bundesanstalt | PTB
The National Metrology Institute | Braunschweig & Berlin

EMN Advanced Manufacturing | Open Stakeholder Meeting
Braunschweig | October 23rd, 2024

PTB

ADVANCED MANUFACTURING



Metrology in a nutshell | Approach

- **Innovation impact of metrology in quality of live for …**
  - … innovation and prosperity ▪ … digital transformation
  - … health and safety ▪ … security and resilience
  - … energy, climate, and environmental protection

> *"We ensure that people and organizations can trust measurements."* *PTB Philosophy*

- **Our common strategy: measurement infrastructure**
  - Supplying precision metrology for SI units
  - Quantum technologies for next-generation devices
  - Metrology for a digitally-transformed world
  - Supporting world's energy needs for tomorrow
    - ▶ **Metrology is making a critical difference**



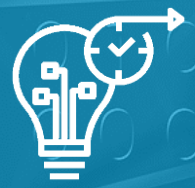
Agenda | Three perspectives of future metrology



PTB's metrology legacy
The innovation perspective



Metrology & digitalization
The international perspective



Frontiers in metrology
The system's perspective

PTB

PTB's metrology legacy

The innovation perspective



PTB

PTB's metrology legacy | Early beginnings

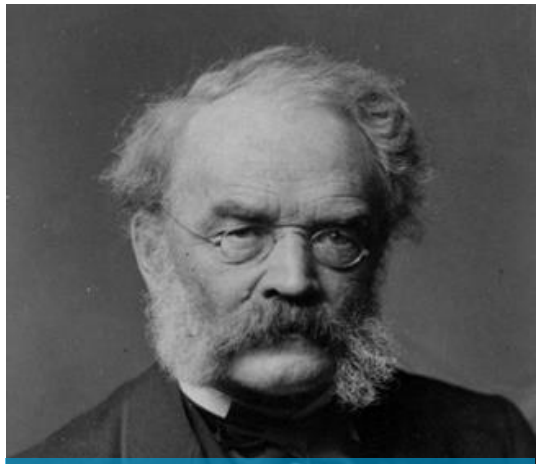
- **Metrology for science and industry for 135 years!**
  - Innovation in science ◄ ► Hermann von Helmholtz
  - Progress in industry ◄ ► Werner (von) Siemens



„Observatory" of PTB at Marchstrasse in 2017

Metrological innovations are in the DNA of PTB


Hermann von Helmholtz


Werner von Siemens

PTB's metrology legacy | A chronology in a nutshell

Reliability and confidence in the accuracy of measurements

- Cradle of metrology in Berlin ◄ ► Vision and values of our pioneers
- Accuracy, objectivity and passion ◄ ► Transformation to the PTB of tomorrow



1887 foundation PTR

… based on ideas by Werner von Siemens and Hermann von Helmholtz in Berlin



1950 foundation PTB

... at the Braunschweig site, at the former German Research Institute for Aeronautics



1953 „Institut Berlin"

… the PTR Institute in Berlin-Charlottenburg is integrated into PTB



1990 re-united

… by taking over the metrology division of the ASMW* of former GDR



2019 Revision of SI

… implemented with the support of PTB in the international metre convention with 110 nations

* Amt für Standardisierung, Messwesen und Warenprüfung (Office of Standardization, Metrology and Goods Testing)

PTB today | Our sites & our departments

Locations & structure

- Braunschweig & Berlin







- Departments of PTB

- Mechanics & Acoustics
- Electricity
- Chemical Physics
- Optics
- Precision Engineering
- Ionizing Radiation
- Temperature & Synchr. Radiation
- Medical Physics
- Legal & international metrology
- Technical & Administrative Services

PTB today | PTB in numbers 2023



2.116
Employees

234
PhD students





121
Trainees



48
International guest researchers



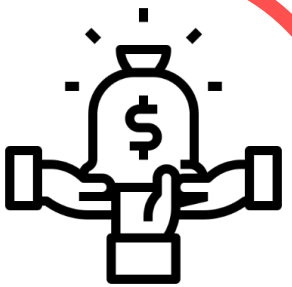
296 Mio €
Expenditure



14,7 Mio €
Income



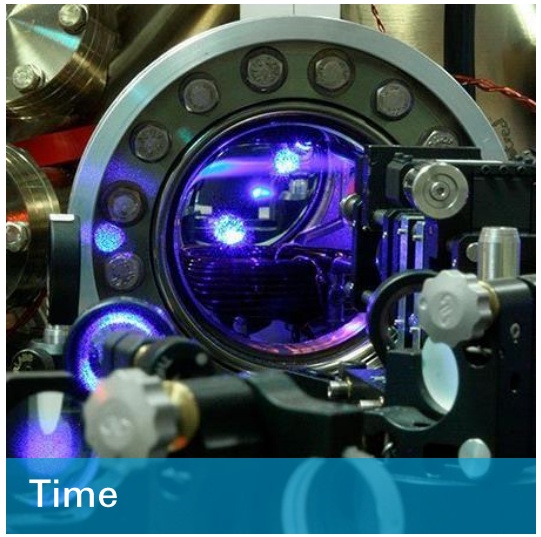
23,8 Mio. €
International cooperation

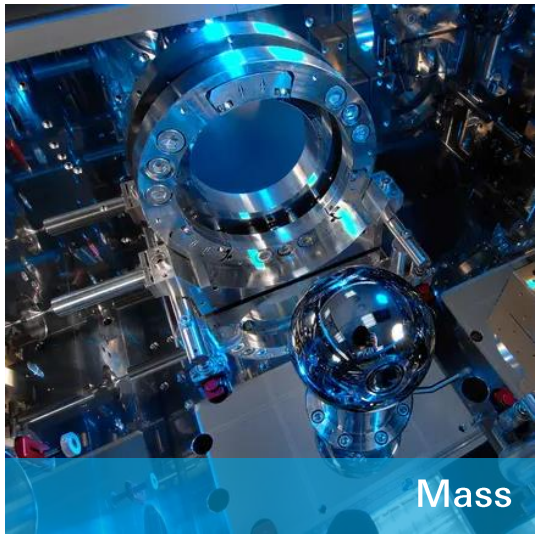


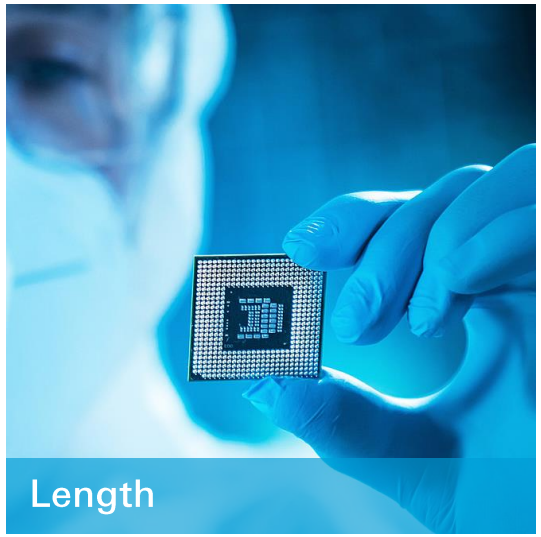
25,9 Mio. €
Expenditure on third-party funding

PTB today | Tasks in precision metrology

- **Science of precision measurement**
  - Development and dissemination of SI
  - Fundamental cutting-edge metrology research
  - Accuracy, comparability and innovation
    - ▶ Metrology for society
- **Advancement of legally-regulated metrology**
  - Harmonization, calibration, admissions
  - Objectivity, reliability, enabling transformation
    - ▶ Metrology for industry
- **Strategic further development**
  - Continuously rethinking metrology
    - ▶ Metrology of tomorrow



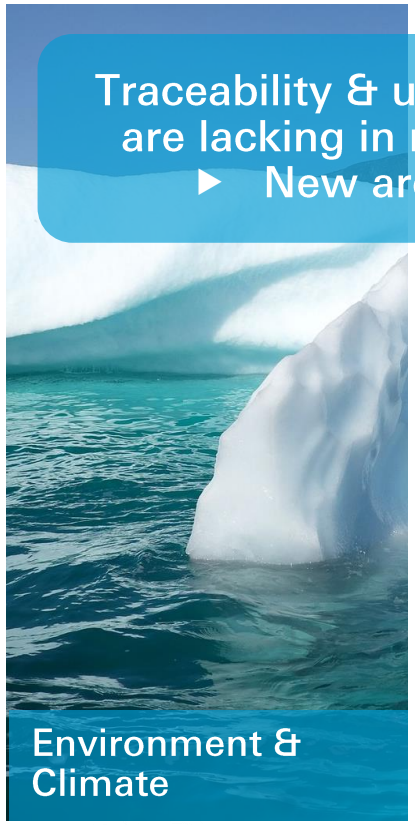






PTB today | A transition to new frontiers in precision metrology

- **Major technical and societal challenges require innovation & transformative change**
  - Interdisciplinarity for technological competence ▶ Project orientation
  - Preliminary research for tomorrow's metrology ▶ Complex, advanced systems













Metrology in transition | Energy transition and climate crisis

- **Sustainability | Urgent needs**
  - Efficient use of renewable energies ▶ Resource efficiency
  - Storage and distribution of energy ▶ Resource conservation
  - Circular material economy
    - ▶ Resource sufficiency
  - Biodiversity and ecosystems
    - ▶ Resource consistency

- **Metrology supports sustainability by …**
  - … efficiency measurements
  - … monitoring resource changes
  - … precise life cycle analysis
    - ▶ Metrology makes a difference

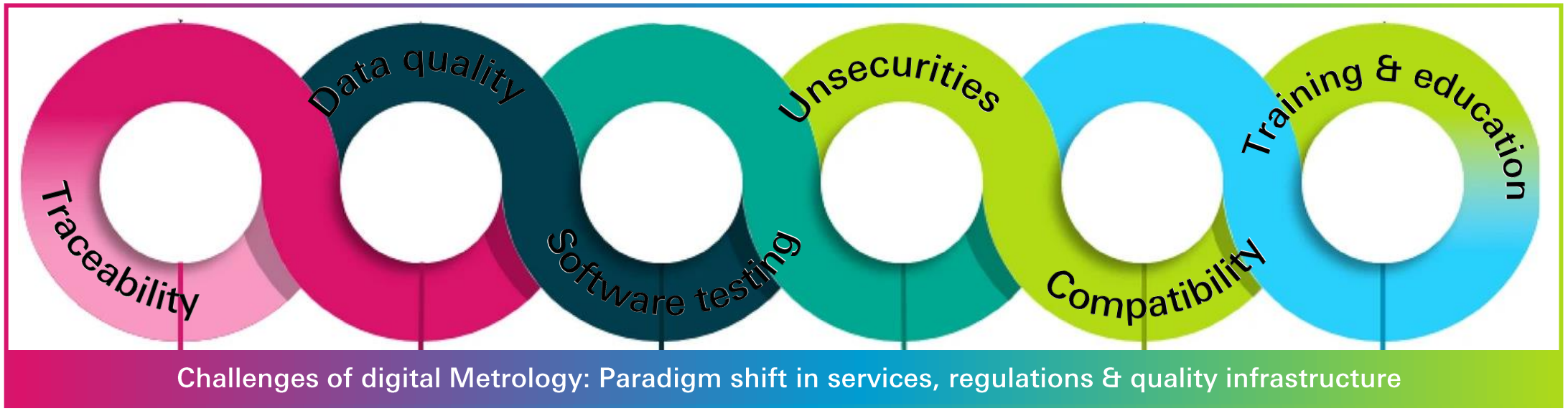
Advanced materials & smart product design is needed for circular economy



Metrology in transition | Facets of digitalization

- **Fundamental key areas where digital metrology is necessary**
  - Transforming metrology services ▶ Digital quality infrastructure
  - Research for digital traceability ▶ Communication systems
  - Digital system measurements ▶ Virtual metrology & digital twins
  - Establishment of metrological data analysis ▶ Large data bases & AI

Manufactured components and products need digital services & inspection



Metrology in transition | Transition to complex systems

- **Networked systems combined with intelligent digitalization**
  - Combing single units into **complex systems** with **emerging properties**
    - Hyper-connected and optimized **intelligent** systems
    - Interplay with **digital & AI algorithms**
    - **Methods to measure systems**

- **The system's perspective**
  - Shift in functionalities, focus & processes
    - From sensors to **sensor networks**
    - From analogue to **digital units**
    - From independent to **embedded data**
    - **Metrology of complex systems**

Smart manu-facturing systems shape future work and cities



An example of a complex system with heterogeneous sensor networks: Smart city of the future © blog.getmyparking.com/

Metrology in transition | Transition to industry 5.0

- **The fourth industrial revolution | The technology-driven digital revolution**
  - **Connecting digital** & **conventional** processes & services of manufacturing
  - **Intelligent networking** of machines by communication technologies
    - Flexible production
    - Extensive use of data
    - Customer-centric solutions

- **The upcoming 5th industrial revolution**
  - Approaches to **sustainable production**
  - **Agility & resilience** in new technologies
  - **Collaborative interaction** between humans and machines
    - **Metrology enables Industry 5.0**

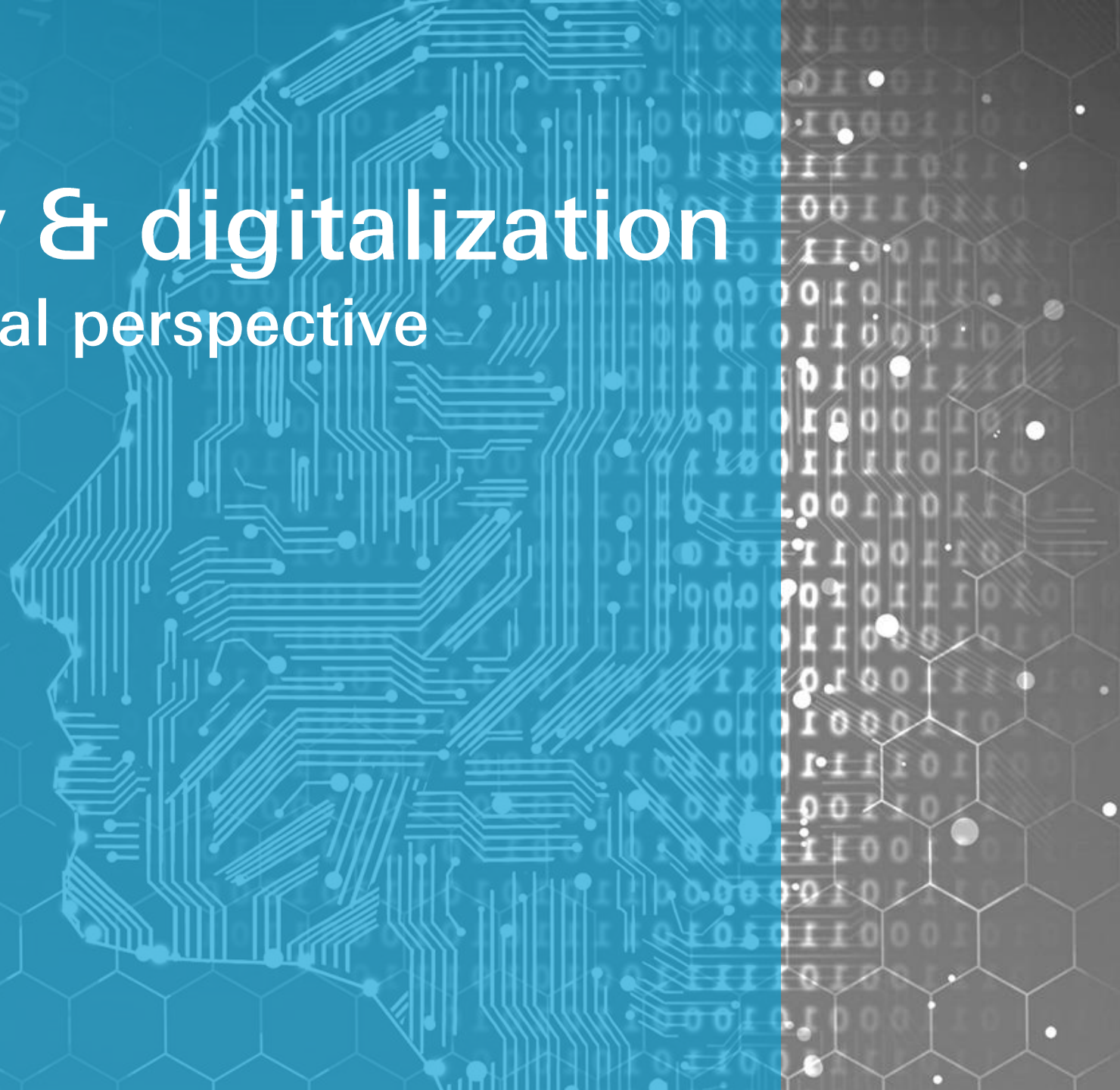
The transition from industry 4.0 to 5.0 require smart & automized factories



Industry 5.0 adds a human centric perspective to sustainable and resilient production © www.enerquire.com/

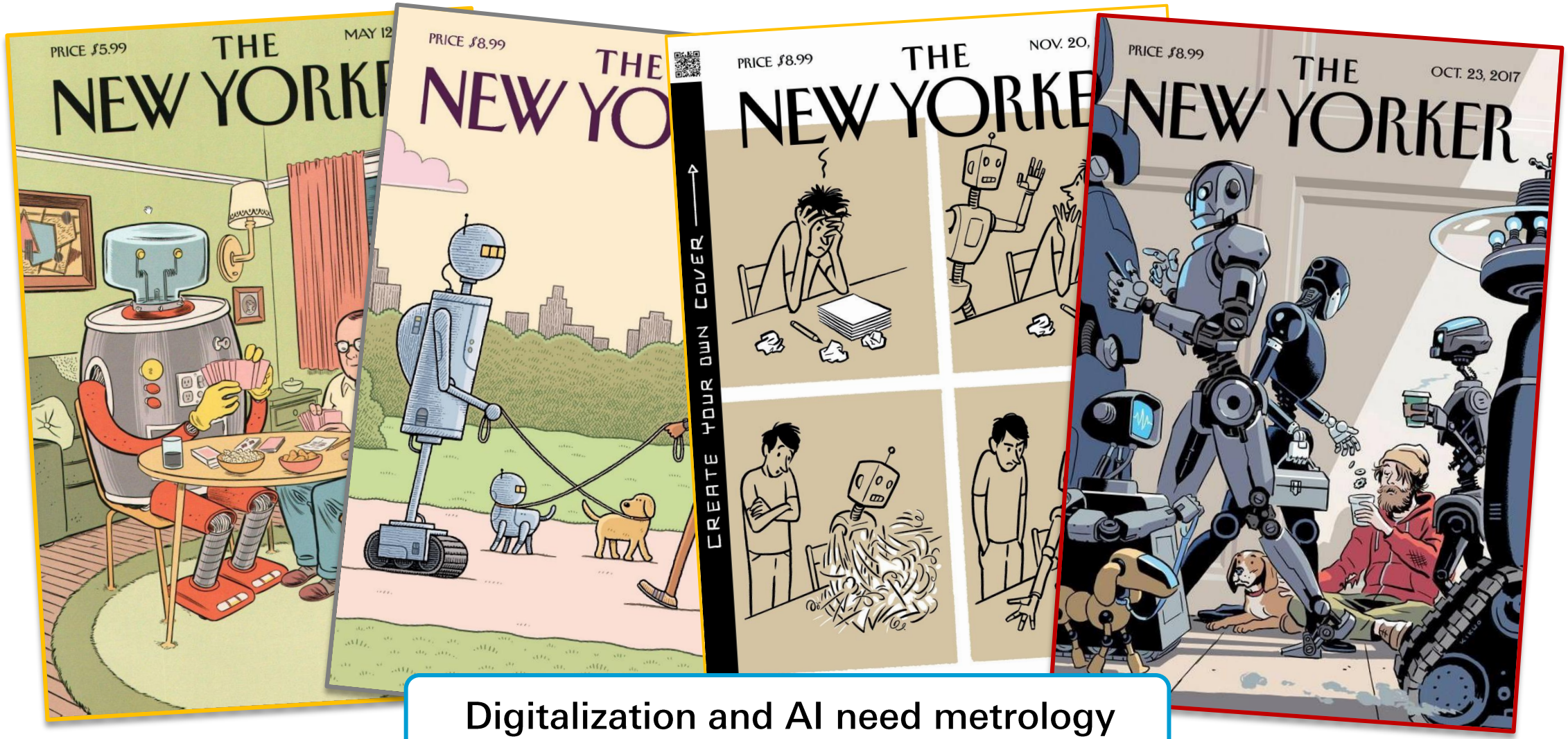
Metrology & digitalization

The international perspective



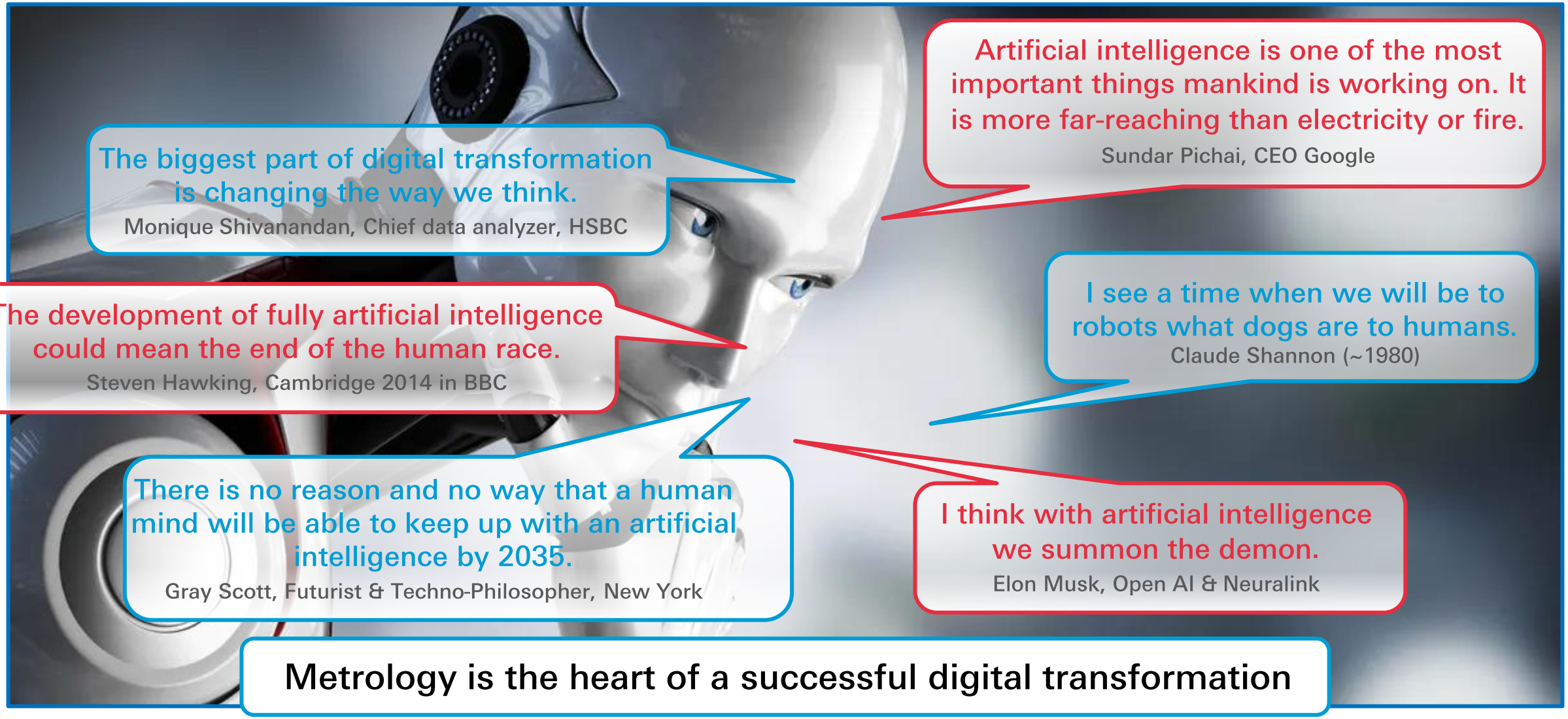
PTB

Digital Transformation | Facets of digitalization



Digitalization and AI need metrology

Digital Transformation | Facets of digitalization



Metrology is the heart of a successful digital transformation

Digital Transformation | Facets of digitalization

- **Ask the next generation**
  - In 20-30 years …



Metrology needs to be an anchor of trust also in the digital world

Digital Transformation | Key challenges for metrology

Obvious challenges

Develop new services & products

Digitalize internal processes & implement tools



Hidden challenges

Develop a holistic digitalization strategy & define a north star

Develop implementable roadmap goals

Ability to include external capabilities

Change the mindset of QI & the way of working

Streamline digitalization & AI in all facets of metrology

Ensure top leadership commitment

Responding to evolving digital needs

Forum MD concept and terms of reference



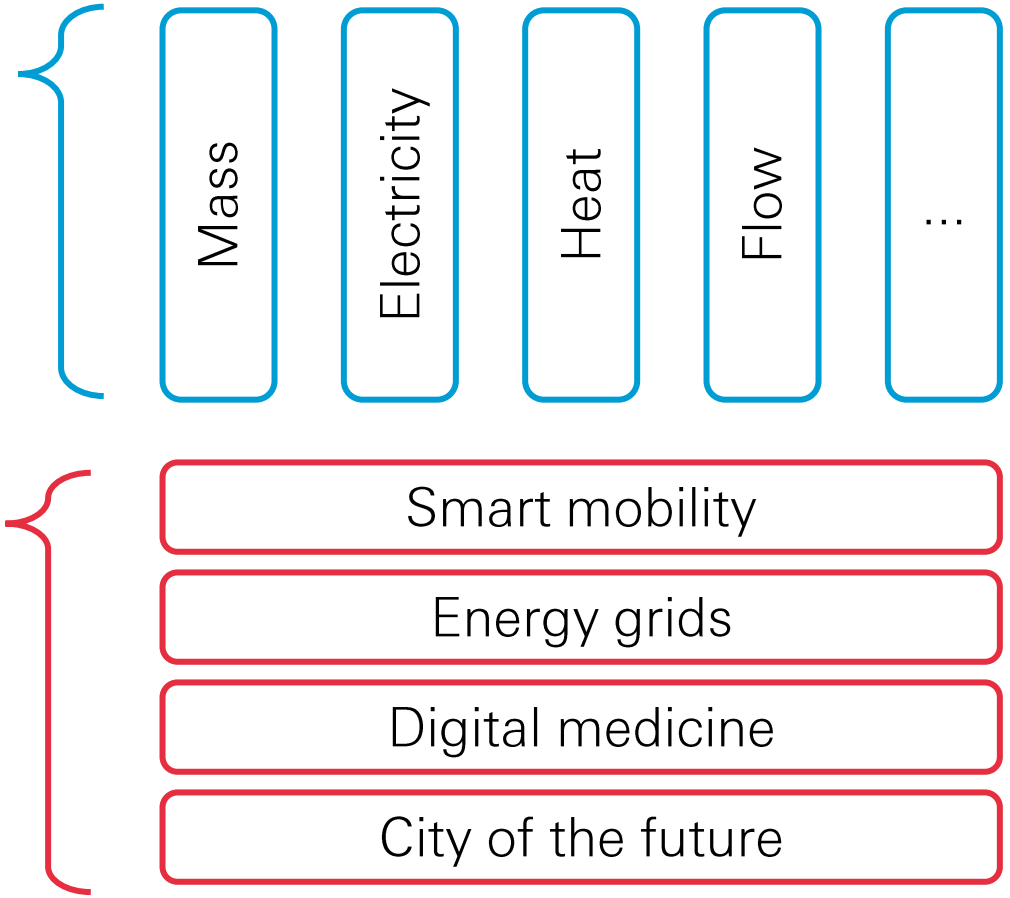
Why a horizontal forum? | Facing digital needs in metrology

Classical metrology fields

- Digitalization in classical metrology fields as mass, electricity, heat, flow, …
  - ▶ **Components and devices in regulated areas of legal metrology**

Emerging fields of metrology

- Questions on traceability, uncertainties, and on harmonization
- Combination of digitalization with AI
  - ▶ **Digitalization is relevant for all fields of metrology world-wide**
  - ▶ **International task of metrology**



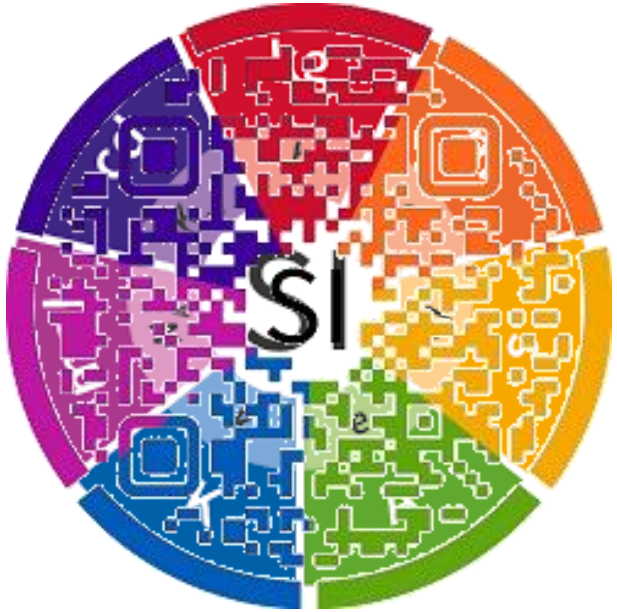
The idea of Forum MD | CIPM Vision on digitalization

CIPM Vision | Transforming the SI for a Digital World

„[...] ensure that the Metre Convention naturally extends its role as the globally accepted anchor of trust for metrology into the digital era [...]

Resolution 2 of the 27th CGPM (2022)

- A globally accepted **digital representation of the SI**
- Adoption of **FAIR principles** in digital metrological data
- Facilitating use of **digital certificates**
- **Machine-actionable functions** of the SI
  - ▶ Digital transformation of all important services of BIPM
  - ▶ Horizontal theme of QI ▶ Formation of a horizontal forum
  - ▶ Extension to emerging digital needs of CIPM members



Forum MD | Mission and Structure of the Forum

The terms of reference of Forum MD

To advise CIPM on the SI Digital Framework and the wider implications of the global digital transformation for metrology and for the **international digital QI**

- Adoption of **FAIR principles** for metrological data
- Providing metrological input in **emerging areas**
- Create **authoritative digital reference** for core SI
- **Digitally transform services & products** of BIPM
- Consider implications of digitalization on **CIPM-MRA**

Objective 1:
To harmonize internal processes of digitalization of NMIs, CCs, RMOs, BIPM

Objective 2:
To act as a forum to exchange information and to create **synergies and opportunities for collaboration** in this field

Forum MD | Participation institutions

- **Membership criteria adopted from general CIPM rules**
  - Members should be recognized internationally as **expert in the field**
  - Members should **demonstrate competences** by a record of international activities
- **Horizontal nature of F-MD**
  - Inclusive participation: **Observers are welcome!**
  - Invitation of experts
  - Inclusion of liaisons



Forum MD | Task and working groups

Establishment of 6 Task Groups and 3 Working Groups March 2024

- Chairs Cornelia Denz (PTB), Georgette Macdonald (NRC), Hector Laiz (INTI)

TG AI
Secure & trustworthy AI
Louis Wright (NPL)

TG DQ
Data quality in metrology
Mark Ballico (NMIA)

WG CC
Coordination for CCs
Peter Blattner (METAS)

TG FM
FAIR for metrology
Robert Hanisch (NIST)

TG H-DCC DRMC
Harmonizing DCC & DRMC
Martin Koval (CMI)

WG RMO
Coordination RMOs
Nikita Zviagin (VNIIM, interim)

TG MS
Metrological semantics
Ryan White (NRC)

TG SIDF
SI-digital framework
Anna Cypionka (BIPM)

WG S
Strategy
Cornelia Denz (PTB)

Forum MD | Task and working groups

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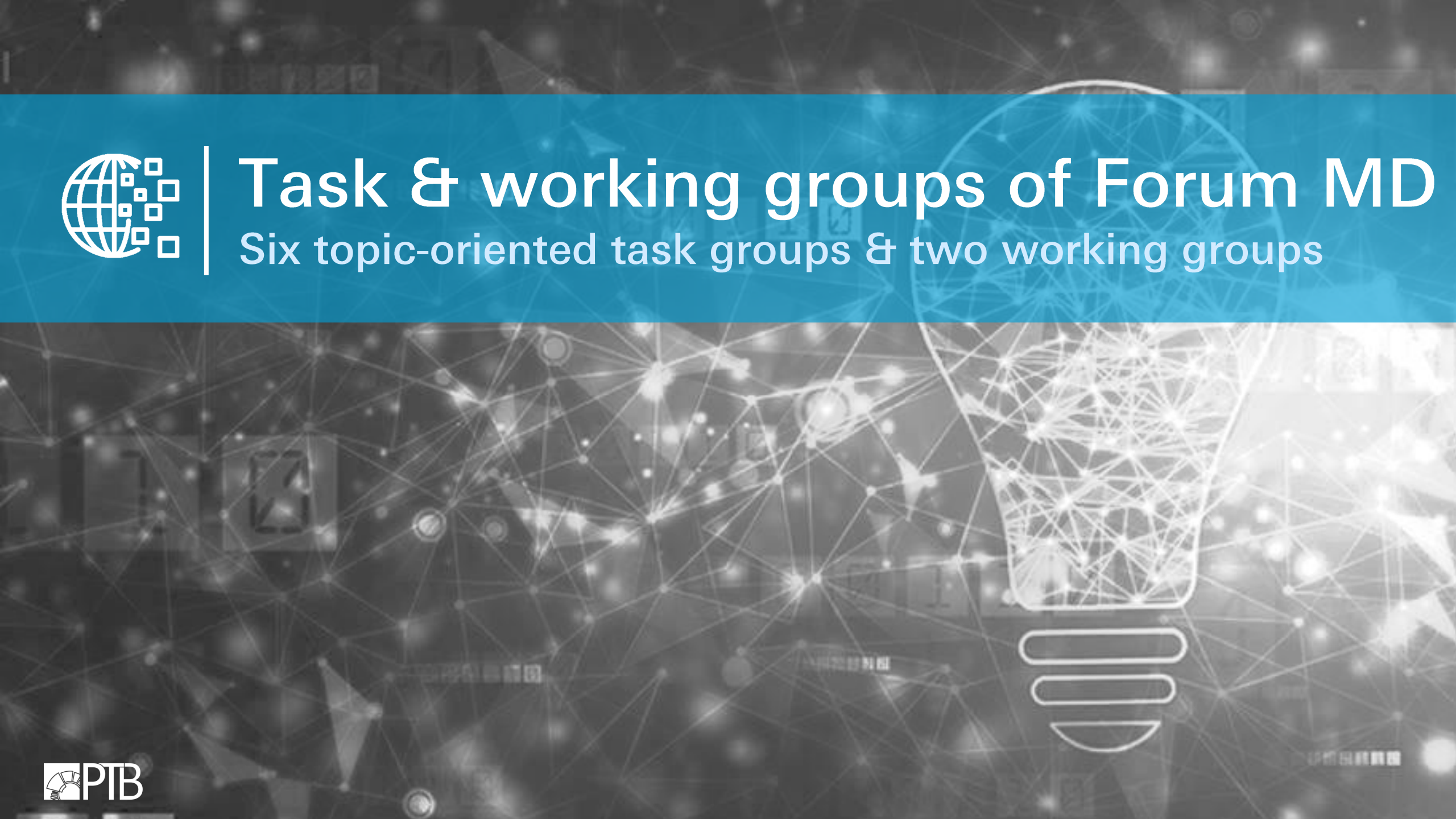
TG H-DCC DRMC
Harmonizing DCC & DRMC
Martin Koval (CMI)

WG RMO
Coordination RMOs
Nikita Zviagin (VNIIM, interim)

TG MS
Metrological semantics
Ryan White (NRC)

TG SIDF
SI-digital framework
Anna Cypionka (BIPM)

WG S
Strategy
Cornelia Denz (PTB)



Task & working groups of Forum MD

Six topic-oriented task groups & two working groups

PTB

Forum MD | TG SI-digital framework

Implementation of fundamental new digital metrological services

Purpose: Support the technical implementation of the SI Digital Framework (SIDF) as a user, test & feedback group
- **SI reference point**

Features of SI digital reference point
- Standardized vocabularies for DCC, …
- Coherent persistent identifier scheme
- Web services for software agents
- Web interfaces for humans

Provide technical and **strategic input**

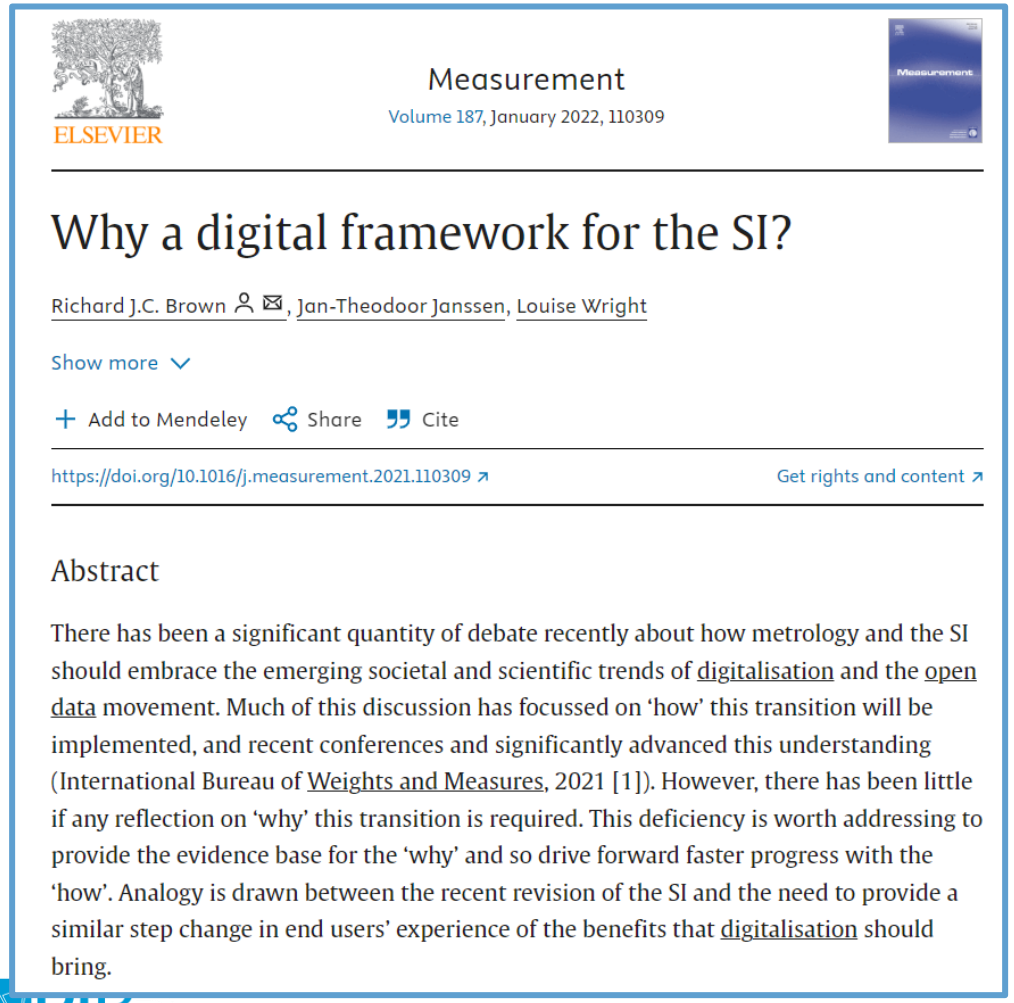
Collaborate with CCU to **ensure alignment** of the SIDF and the SI brochure

Advise the BIPM team & Forum MD

Review the work plan for the BIPM Digital Transformation Team

FORUM-MD | TG SI-digital framework

Implementation of fundamental new digital metrological services



ELSEVIER

Measurement

Volume 187, January 2022, 110309

Why a digital framework for the SI?

Richard J.C. Brown, Jan-Theodoor Janssen, Louise Wright

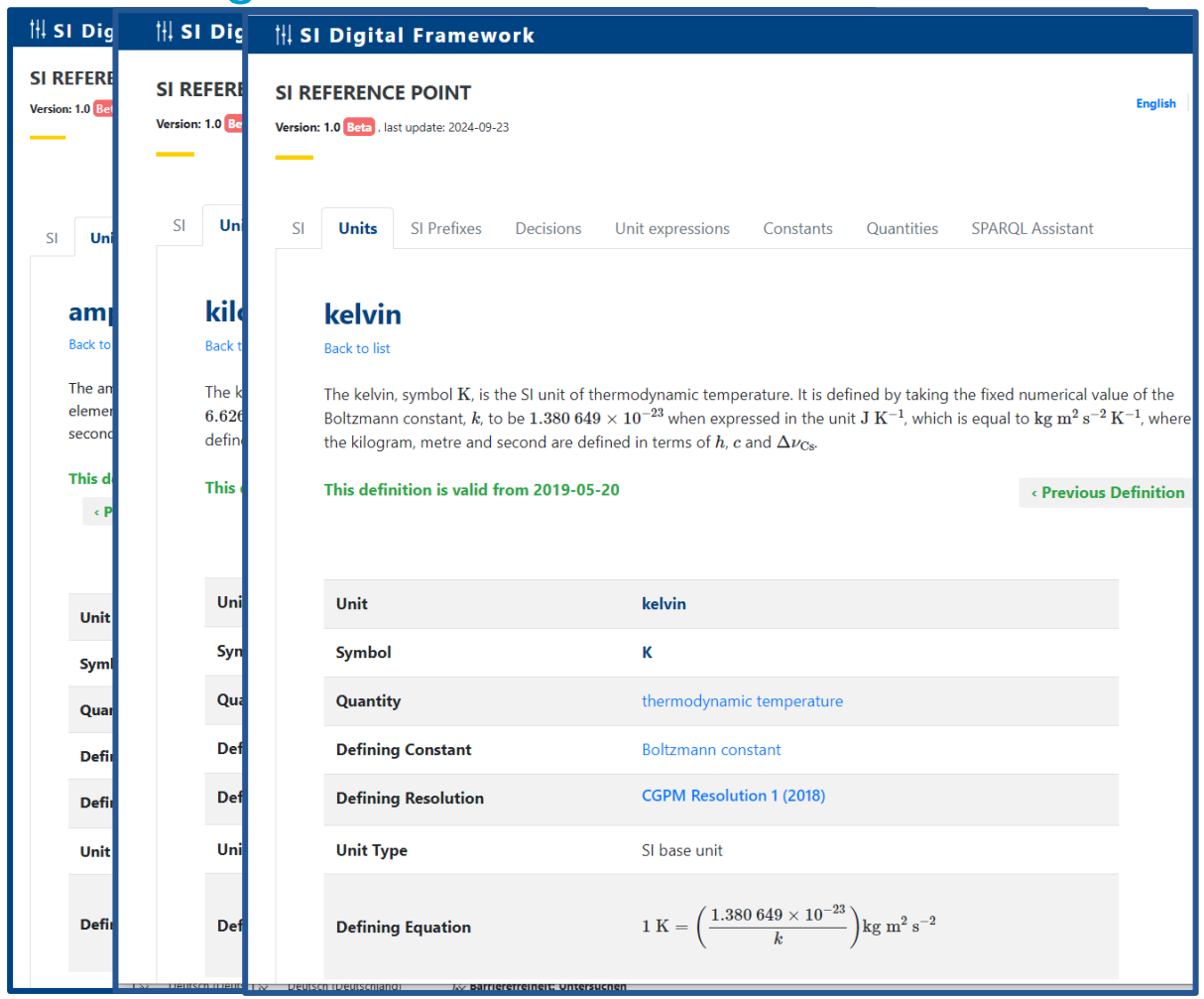
Show more

Add to Mendeley Share Cite

https://doi.org/10.1016/j.measurement.2021.110309 Get rights and content

Abstract

There has been a significant quantity of debate recently about how metrology and the SI should embrace the emerging societal and scientific trends of digitalisation and the open data movement. Much of this discussion has focussed on 'how' this transition will be implemented, and recent conferences and significantly advanced this understanding (International Bureau of Weights and Measures, 2021 [1]). However, there has been little if any reflection on 'why' this transition is required. This deficiency is worth addressing to provide the evidence base for the 'why' and so drive forward faster progress with the 'how'. Analogy is drawn between the recent revision of the SI and the need to provide a similar step change in end users' experience of the benefits that digitalisation should bring.



SI Digital Framework

SI REFERENCE POINT

Version: 1.0 Beta, last update: 2024-09-23

English

SI | Units | SI Prefixes | Decisions | Unit expressions | Constants | Quantities | SPARQL Assistant

kelvin

Back to list

The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant, k, to be $1.380\,649 \times 10^{-23}$ when expressed in the unit $\mathrm{J\,K^{-1}}$, which is equal to $\mathrm{kg\,m^2\,s^{-2}\,K^{-1}}$, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{\mathrm{Cs}}$.

This definition is valid from 2019-05-20

‹ Previous Definition

Unit	kelvin
Symbol	K
Quantity	thermodynamic temperature
Defining Constant	Boltzmann constant
Defining Resolution	CGPM Resolution 1 (2018)
Unit Type	SI base unit
Defining Equation	$1\ \mathrm{K} = \left(\frac{1.380\,649 \times 10^{-23}}{k}\right)\mathrm{kg\,m^2\,s^{-2}}$

Forum MD | TG FAIR for Metrology

Implementation of the FAIR principles in a metrological context



Objective 1: Improving FAIRness of metrology data for reproducibility & transparency

- **Streamline** key comparisons
- Inclusion of community-wide **metadata standards**

Objective 2: Examine research practices & make recommendations

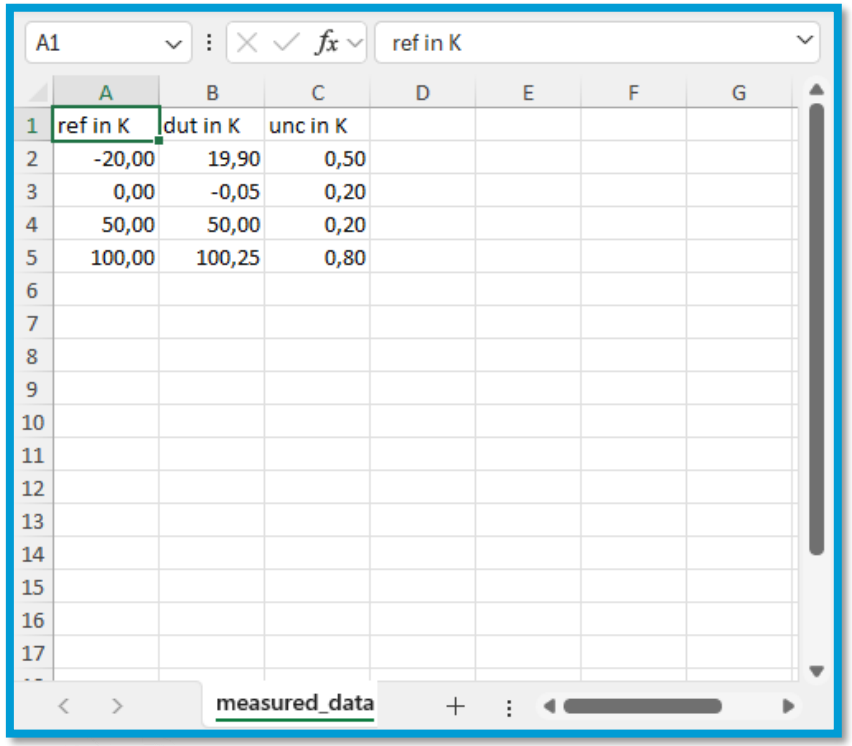
- Increase the value of FAIR metrology to the **broader community**
- Prepare survey

Forum MD | TG FAIR for Metrology

Implementation of FAIR principles in a metrological context

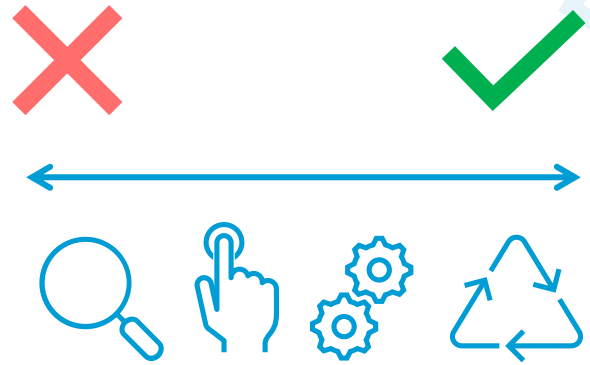
My measurement data can be found on the shared internal folder cal_data/2024_10_17/data.xlsx

https://some.pid.example/dataset_1a4fb87



	A	B	C
1	ref in K	dut in K	unc in K
2	-20,00	19,90	0,50
3	0,00	-0,05	0,20
4	50,00	50,00	0,20
5	100,00	100,25	0,80

Findable, accessible, interoperable, reuseable




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Forum MD | TG Harmonizing DCC & DRMC

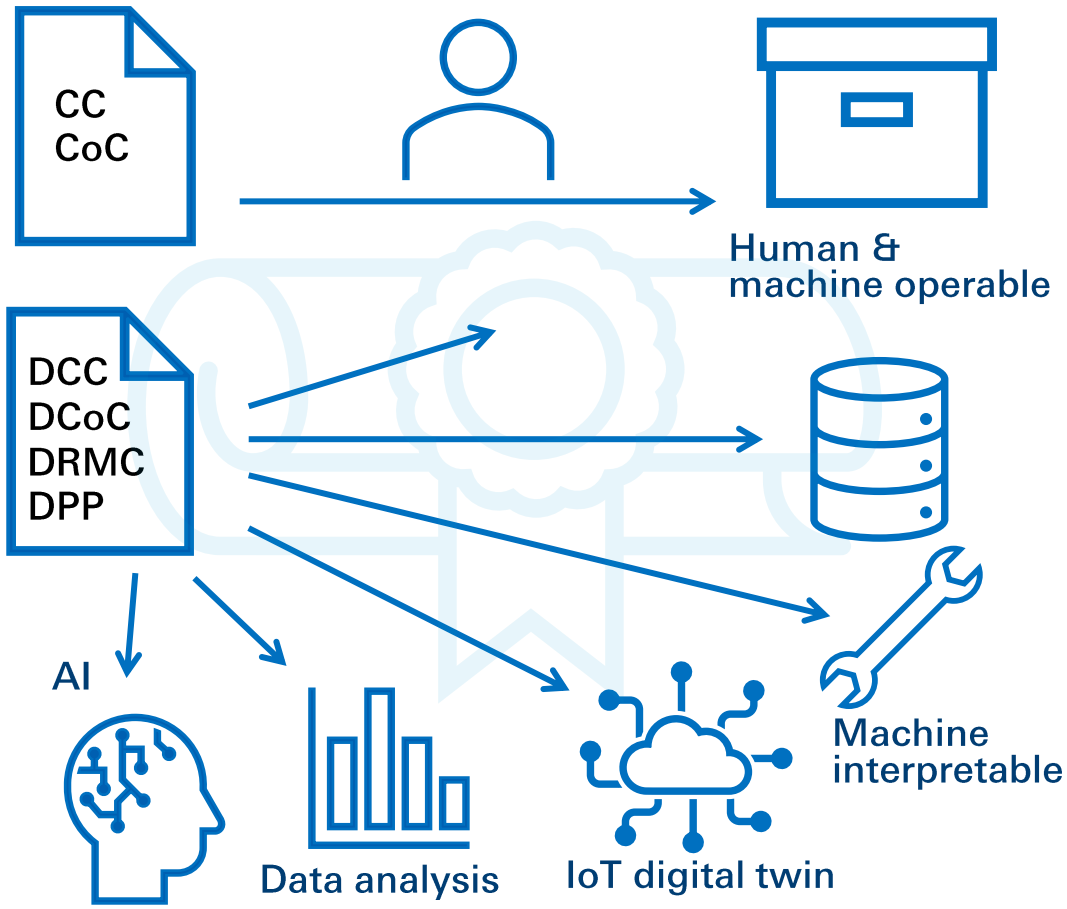
- Develop user stories and value propositions to disseminante DCC et al.

Purpose: Harmonize procedures, improve understanding, prepare guidance documents

Objective 1: Identifying stakeholder needs

Objective 2: Developing common understanding & value proposition

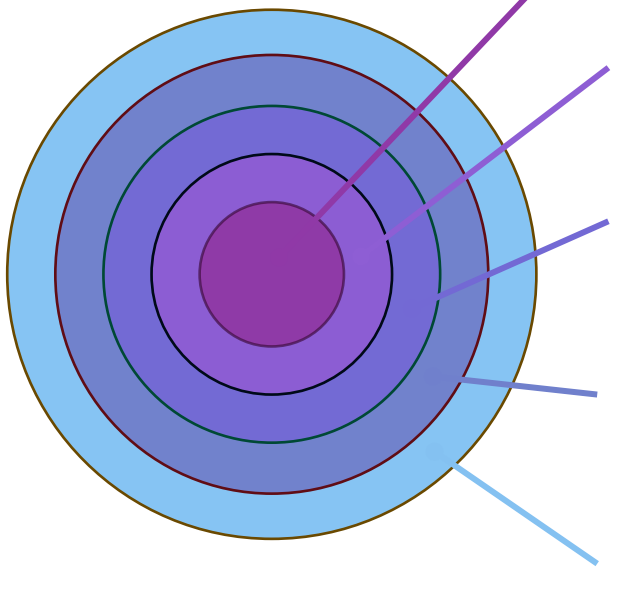
Objective 3: Harmonizing DCC/DRMC & promoting DCC/DRMCs by user stories



Forum MD | TG Harmonizing DCC & DRMC

Example: Structure and data-model of a DCC

- Onion- or cell-like structure



Administrative data*

Results of the Calibration*

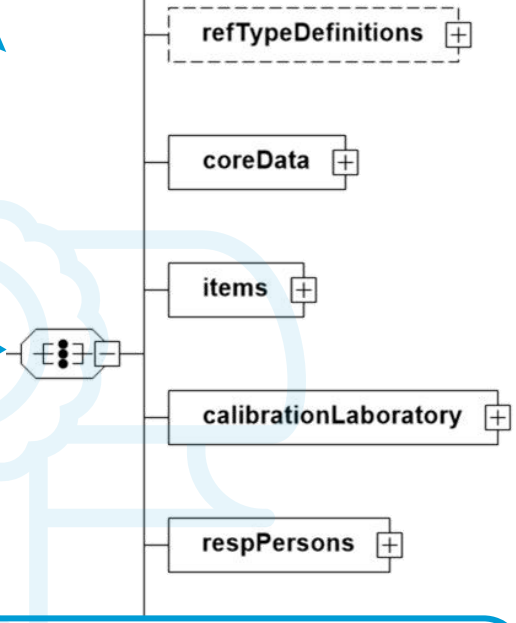
Comments

Document

Signature/Seal

If you thought that a PDF is a digital calibration certificate, think again!

https://blog.beamex.com/



DCC is the **"MP3 of metrology"**

- Revolutionizing processing industry as a flexible, secure game changer

Forum MD | TG Secure and trustworthy AI

Respond to the growth of AI

Metrology needs AI for effectiveness

- Address measurement challenges
- Improve e.g. conformity assessment

AI needs metrology for confidence

- Demonstrate traceability of outputs
- Define uncertainties to measurands
- Define requirements for data quality

Purpose: Providing guidance to CIPM on

- use of AI for metrological purposes
- provision of metrological services by AI

- Assessment of existing legislation
- Metrological data becoming “ready for AI”
- Identification of standards governing AI
- Interaction with international organizations

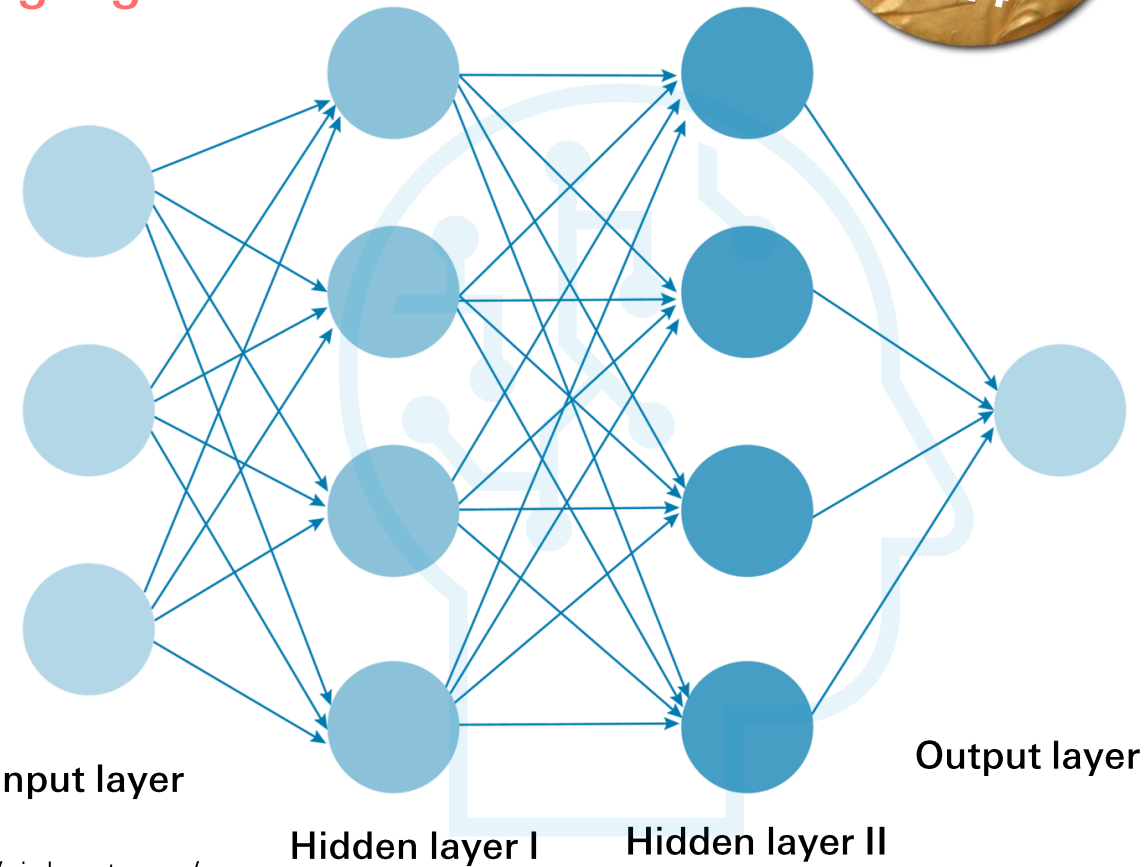
EU AI Act §15 (2): metrology authorities as stakeholders on „[...] how to measure the appropriate levels of accuracy and robustness [...]”



Forum MD | TG Secure and trustworthy AI



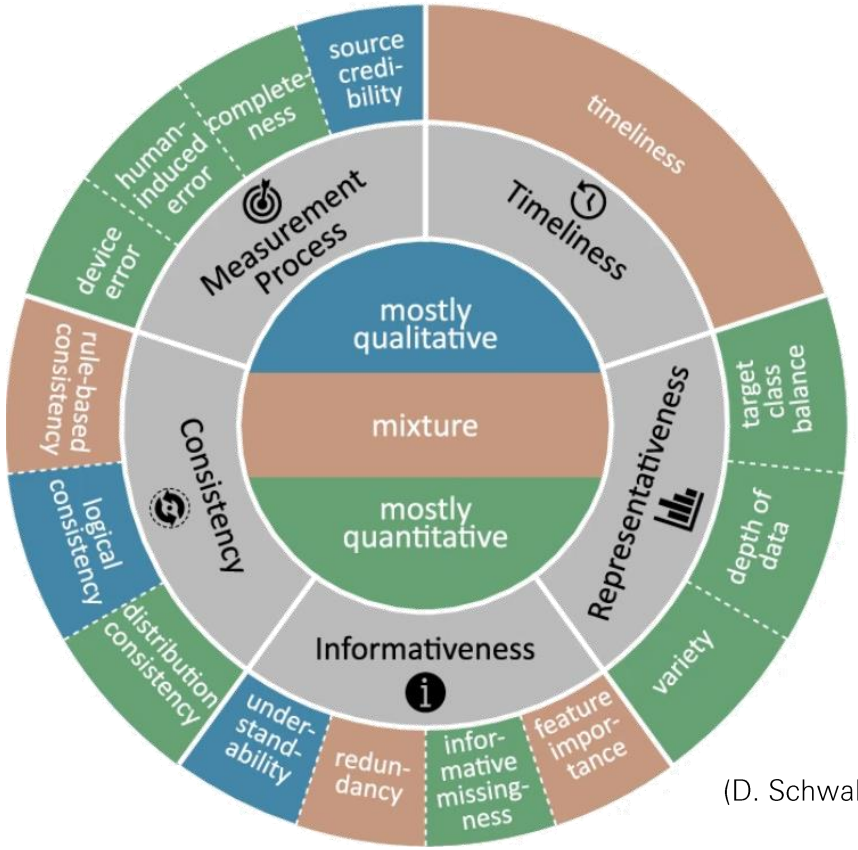
- **Example | Transparency & understanding of algorithms**
  - **Neural network classes defined by learning algorithms**
    - Supervised (deep) learning
      (Hebb 1949; Perceptron: Rosenblatt 1961)
    - Competitive (self organized) learning
      (Kohohen 1984)
    - Fully connected (deep) learning
      (Hopfield 1986; Boltzmann Machine: Hinton 1985)
    - Unsupervised, free learning
      (Adaptive resonance: Carpenter, Grossberg 1987)
  - **Today's data intensive approaches**
    - Neuromorphic computing
    - Convolutional neural networks
    - Reservoir computing



https://aiplanet.com/

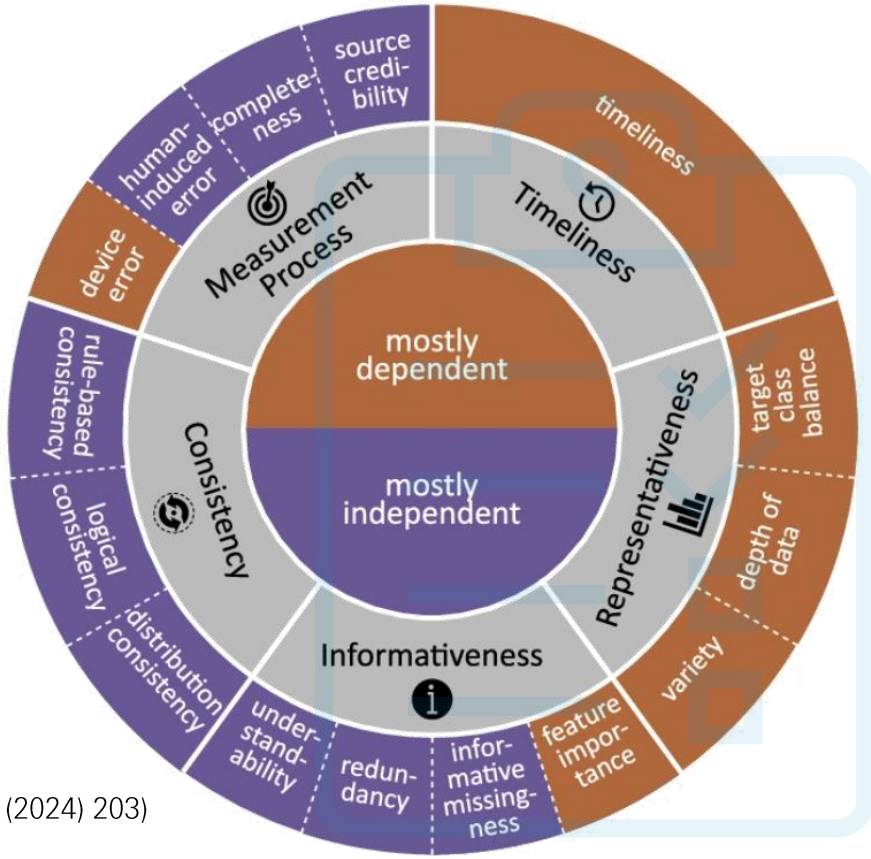
Forum MD | TG Secure and trustworthy AI

Example | Metric categories for assessing data quality in medicine



Dimensions along the properties
quantitative qualitative

(D. Schwabe et al., npj Digit. Med. 7 (2024) 203)



Dimensions along the properties
dependent independent

Forum MD | TG Strategy

- **Strategy of Forum MD: Propose a long-term vision for Forum MD**
  - Exchanging information and coordinating activitites

Monitor and react to relevant developments in digitalization

Ensure an **effective linkage** between organizations in liaison

Advise the Forum MD on its **optimal operational structure**

Prepare plenary **meetings** and propose **conferences** and other **events**



Events and activities

Workshops, meetings & dissemination

Events of Forum MD | Workshops

Workshop Metrological Traceability, IMEKO August 28th 2024

- Co-organized by the CIPM Forum MD in partnership with IMEKO TC6 (Digitalization), TC8 (Traceability in Metrology), and TC21 (Mathematical Tools for Measurements)
  - Organizers: Blair Hall & Frank Härtig, about 80 participants

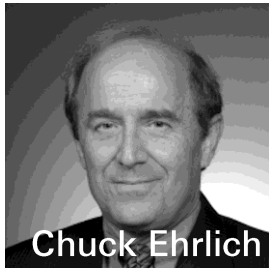


Events of Forum MD | Workshops

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  - Organizers: Blair Hall & Frank Härtig, about 80 participants
- **Session 1: Foundational principles of metrological traceability** and how those principles can be architecturally modelled and implemented in the international quality infrastructure
- **Session 2: Outlook into the future** how the core concepts of traceability are being applied to digital frameworks. With a special focus on new developments in digital metrology.

- **Speakers**













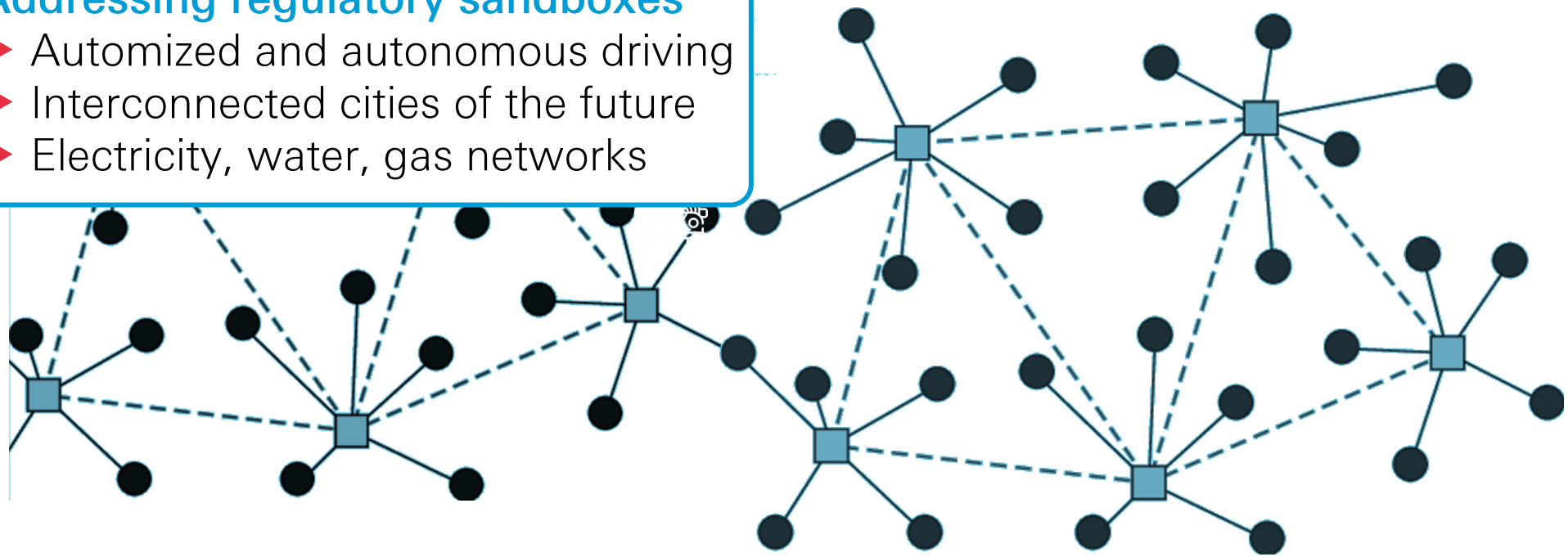




Events of Forum MD | Workshops

- **Online WS Complex sensor networks, February 11th & 12th 2025**
  - Complex sensor networks of multiple (heterogeneous) sensors
    - **Organizers** Cui Shan, NMC and Chiyun Cho, KRISS, with Martin Koval, CMI, Sascha Eichstädt, PTB, Narin Chanthawong, NIMT, Aldo García González, CENAM

Addressing regulatory sandboxes
- Automized and autonomous driving
- Interconnected cities of the future
- Electricity, water, gas networks



Events of Forum MD | Workshops

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- **2nd general meeting of Forum MD**
  - February 19, 2025: Workshop on **Emerging Topics in Digitalization of Metrology**
  - February 20 and 21, 2025:
  - Plenary reports of TGs & WGs, Reports of liaison group



Events of CIPM | Focus themes on digitalization

- **May 21-22, 2025: Symposium 150 years of BIPM / CIPM**
  - New opportunities from horizontal themes in metrology
    - Celebration 150 years at UNESCO headquarters Paris

    - Session 1: Climate and Environment
    - Session 2: Quantum Technologies
    - Session 3: **Digital Transformation**
    - Session 4: New definition of the second
    - Session 5: Metrology for future revolutions
    - **Artificial Intelligence** ▸ Quantum in Biology
    - Metrology for High Energy Particles ▸ **Open Metrology**



Frontiers of metrology

The system’s perspective



PTB

Frontiers of metrology | Metrology for systems

Emerging metrology needs in complex systems

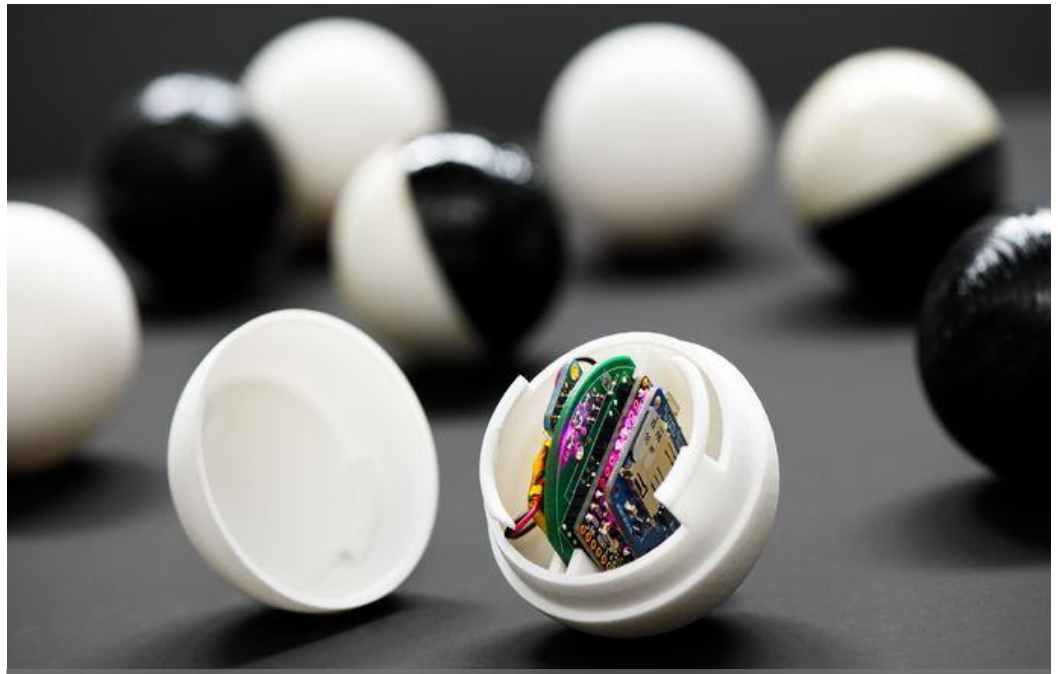
- Extended & strongly coupled sensor networks of next generation
  - From large sensor networks to **sensor swarms** of small, simple sensors

Large heterogeneous sensor networks

- Responsive, adaptive, self-organized
- Uncertainties needs to be defined
- **Self-traceability** by use of massive AI

Examples of sensor swarm applications

- Gas detection wearables for safety
- **Spatio-temporal** climate monitoring
- Sensitive electric / magnetic field det.



Large swarms of sensors can measure more than a single sensor due to complex interaction @ Phoenix D

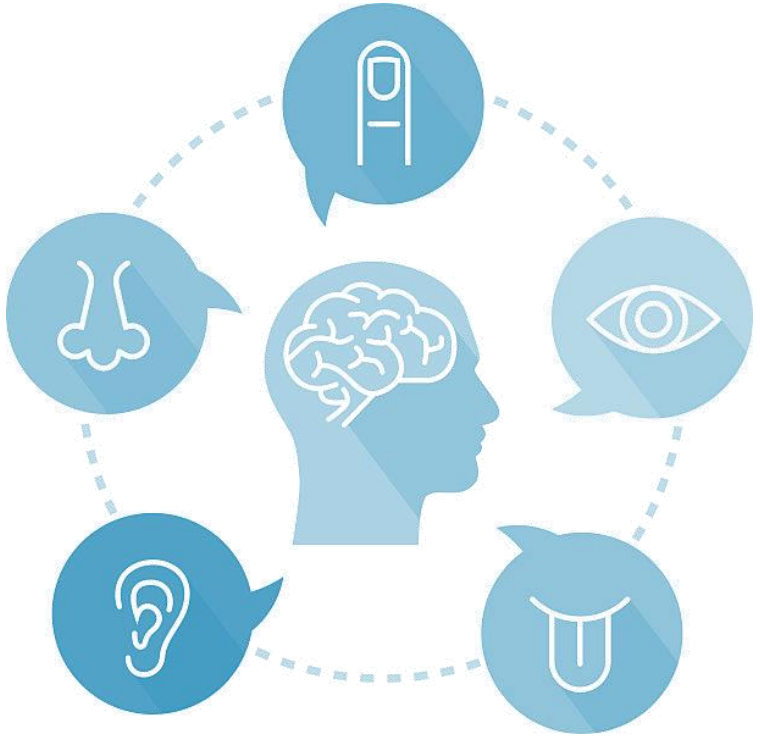
Frontiers of metrology | Metrology for systems

Emerging metrology needs in sensory and cognitive systems

- Perceptual metrology based on sensors of the human sensory systems
  - Stimuli from a large set as sight, hearing, touch

Digital perceptual measurement approaches

- Translate subjective experiences into objective data by digital tools
- Metrology to **objectivate & quantify** human sensory responses
- **Digital or computer sensing** and responding to environment
- Next generation **perceptual human-machine interactions** need **digital QI**



Frontiers of metrology | Metrology for quantum systems

Emerging metrology needs in quantum technology

Applications in quantum sensors, computers, communication

- **Traceability & characterization** for new technology and devices
- Coordination for a coherent **international quantum ecosystem**

Adressing **quantum industry needs in regulatory sandboxes**

- Development of **benchmarking and standards**
- Establishment of a **quantum quality infrastructure**

Report of BIPM Workshop on Accelerating the Adoption of Quantum Technologies through Measurements and Standards

BIPM – March 21-22, 2024



Summary | Forum Metrology and Digitalization

New approaches of CIPM | Horizontal theme in a new structure

Forum MD brings together experts from different areas of metrology

- Address urgent **metrology questions of digitalization**

Forum MD covers themes by **6 Task Groups:** FAIR data, data quality, metrological semantics, DCCs & DRMCs, SI digital framework, trustworthy AI

Forum MD **complements and intertwines activities** of Consultative Committees & Regional Metrology Organizations

Forum MD covers **all aspects** of metrology with respect to **digital challenges**

- **Understanding & harmonization**
- **Dissemination & interaction**

Summary | Forum Metrology and Digitalization

- **New approaches of CIPM | Horizontal theme in a new structure**

Forum MD & CIPM give answers to the most urgent issues in digitalization by metrological approaches





Accurate

Objective

Passionate

Physikalisch-Technische Bundesanstalt
Das nationale Metrologieinstitut

Prof. Dr. Cornelia Denz

PTB