

Communities of practice in metrology

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Abstract – Digital transformation in metrology will entail digitalisation of work practices in national metrology institutes (NMIs). This article argues that *communities of practice* (CoPs)—informal social structures—play a key role in how NMIs operate, making their dynamics a critical consideration in managing digitalisation. NMI work is empirical in nature, and the knowledge required to perform measurements at the highest level is embedded in practice-based forms within CoPs. However, digitalisation necessitates the development of abstract representations of processes and information. Moreover, scientific knowledge is usually communicated in a formal language using abstract concepts. So, digitalisation of NMI work products may be challenged by the distinction between empirical and abstract modes of knowledge capture. This article explores the conceptual tension between abstract and empirical modes of thought in metrology and the challenge of aligning them in the context of digital transformation. It draws on published anecdotal accounts and the author’s professional experience.

I INTRODUCTION

National metrology institutes (NMIs) are centres of excellence in measurement that operate to the highest standards in their respective economies. Their activities span a range of disciplines, naturally organising into broad categories that subdivide into specialised areas—often mirroring the structure of the International Committee for Weights and Measures (CIPM) Consultative Committees. For instance, an NMI’s Electricity and Magnetism section might include groups of people responsible for different DC and AC quantities.

Within NMIs, the practice of metrology has distinctive characteristics compared to other scientific organisations. Metrologists typically work in a specialised area and develop a high level of expertise. They often remain in the same field for extended periods—sometimes for their entire careers. Depending on the size of the institute, they may be somewhat isolated from colleagues in other branches. Moreover, opportunities for metrologists to engage with technical peers in counterpart organisations are often limited, as such interactions typically require international travel.

People typically enter an NMI with no prior experience in metrology. Most have undertaken advanced academic studies—often to doctoral level—in a related scien-

tific field, usually with a focus on experimental research. However, the foundational *concepts* of metrology are not generally taught in universities. As a result, new staff acquire metrological knowledge primarily through interpersonal interaction, with experienced metrologists guiding them in understanding the specific aspects of their field. Importantly, this learning process is embedded in the shared experience of metrology in practice, creating a highly pragmatic context for knowledge acquisition. This contrasts with modes of learning supported more directly by a well-defined theoretical curriculum.

This article considers the particularities of metrology groups and the people in them through the lens of certain sociological factors. Addressing social aspects in a field grounded in physical science is relevant now because of the digital transformation recently initiated by the international metrology community. Digitalisation, the driver of digital transformation, is inherently a process of abstraction. It involves the systematic development of logical representations for concepts and processes. Since digital technology operates on strictly logical systems, digitalisation in metrology requires the elicitation and development of abstract models. However, when confronted with informal, practice-based knowledge held within metrological communities, digitalisation faces a significant challenge.

The distinction between abstract and empirical perspectives among scientists is well recognised. However, the tendency toward abstraction is reinforced by the formal language of science, which underpins both the teaching and communication of scientific concepts. Abstract models are powerful representations of physical phenomena; however, their validity ultimately rests on empirical evidence. Of particular interest here is the empirical nature of the work carried out by NMIs, and the practice-based knowledge held by metrologists, which is vital in maintaining the international measurement system. The work of metrologists tends to be grounded in specialised instrumentation, measuring processes, and raw data processing. Unsurprisingly, local, experience-based interpretations of terminology and concepts can develop within small insular groups. These modes of knowledge representation may be difficult to express outside the context in which they developed.

The close-knit teams working together in NMIs exhibit characteristics of Wenger’s concept of a *Community of Practice* (CoP) [1], which builds on earlier work with Lave exploring how knowledge is generated and sustained

through social interaction in shared practice [2]. In a CoP, members engage in a joint enterprise, developing a shared repertoire of tools, language, and routines, as well as a strong collective sense of identity. Active participation in the community is fundamental. Different roles and trajectories of participation can be observed: newcomers typically begin on the periphery of a group and gradually move toward full membership. A distinctive feature of CoPs is that knowledge is often held tacitly, which complicates the communication of ideas in interdisciplinary collaboration.

The remainder of this article explores the nature of NMI groups in relation to key concepts of a CoP and the effect of abstract and empirical modes of knowledge representation. The central question is how to facilitate communication between metrology groups and digital technology experts to support effective digitalisation. The article is an informal account intended to share ideas with managers and leaders guiding the international metrology community toward a successful and fruitful digital transformation. The discussion draws on anecdotal evidence and on the author's experiences working with groups involved in metrology's digital transformation.

II METROLOGICAL COMMUNITIES OF PRACTICE

In a Community of Practice, a group of individuals engage in a common domain of activity and develop practices, terminology, and a sense of identity through sustained interaction [1]. CoPs are likely to be widespread within metrology. These informal groups emerge spontaneously and are sustained through collaboration related to a specific activity, fostering the creation of knowledge within a community. CoPs are not created by formal structures; however, they may be supported within an organisation's framework.

One of the central ideas of a CoP is that knowledge develops as individuals participate in shared activities. Competency is central to this; meaningful knowledge cannot be asserted without participation, making competency and knowledge inseparable. This emphasis aligns closely with NMI work practices, where tasks must usually conform to international standards, such as ISO/IEC 17025, which requires technical competence to be demonstrated [3]. The competency requirement is fundamental to ensuring the reliability of measurements.

Individuals participate in CoPs at different levels and in different roles that evolve as they gain experience and expertise. Newcomers start on the periphery of a CoP, gradually moving inward as they absorb practices and terminology. Individuals contribute to the co-creation of knowledge, language, and understanding within the community as they engage in shared practices. The idea of *negotiated meaning* is central in CoPs, as knowledge is expressed as part of a dynamic and adaptive process. The negotiation of meaning within a CoP will tend to blend new ideas with ex-

isting practice and terminology. So, a newcomer may bring new and useful ideas that contribute to shared activities, but as the meaning of this new knowledge is negotiated, it will be shaped by existing practice and terminology.

The theory of CoPs identifies a duality of *reification* and *participation*, viewing them as complementary features. Reification makes knowledge tangible by codifying it in documents, databases, protocols, and other artefacts to crystallise shared practices and understanding. Participation, on the other hand, provides continuity of meaning over time and across contexts, compensating for the limitations inherent in reification. For example, teachers and students can negotiate meaning from a reified subject curriculum.

The representation of information and knowledge in reified artefacts is an important consideration, because such artefacts are likely to be identified as objects for digitalisation. Reification occurs both inside and outside metrological CoPs. Internally reified artefacts—such as laboratory notebooks, calibration procedures, and data acquisition software—are primarily intended for use within the CoP, although they may also be scrutinised by external parties as part of quality assurance processes. In contrast, work products, such as calibration reports, are primarily for external use. Some reified artefacts originate outside NMIs but are intended to inform internal practice. Examples include documents intended to harmonise terminology (VIM) [4] and provide guidance for best practice in the evaluation and reporting of measurement uncertainty (GUM) [5].

A strong sense of collective identity develops within a CoP, and is likely a feature of metrological communities due to their stability, long tenures, and specialisation. Stability preserves expertise and ensures continuity in measurement science, but the conceptual foundations of practices and terminology held by enduring CoPs may be conservative. Senior members, having invested heavily in their own understanding of terminology and practices, may be unreceptive to alternative perspectives or explanations. When this occurs, communication across the CoP boundary can become challenging.

CoPs may exploit the role of 'brokers' to address communication challenges. Brokers, who have peripheral access to several CoPs, can facilitate connections between them, enabling coordination and even opening up new possibilities for meaning. Brokership arises from an individual's multiple memberships in CoPs and depends on the individual's status and levels of influence within those communities. A common difficulty in establishing shared terminology is often cited by people with a background in information technology (IT) who have had difficulty engaging with metrology teams. In such contexts, the broker role may be valuable. A broker can facilitate the establishment of a terminological common ground, whereas an

outsider, lacking insight into or understanding of a CoP, may struggle to engage effectively.

To sum up, CoPs are likely to be common in NMIs, making an understanding of their general characteristics essential for facilitating interdisciplinary activities related to digitalisation. Metrological CoPs will hold a wealth of detailed scientific and technical knowledge. However, this knowledge may be held in ways that make access to it challenging. A significant amount of information may remain unreified or be reified in *ad hoc* forms—such as process-related knowledge that underpins specialised technical procedures.

III ABSTRACTION AND EMPIRICISM

Scientific knowledge can be thought of in both abstract terms—representing general concepts—and in empirical terms—grounded in observable phenomena and the methods by which they can be observed. Maxwell’s unit systems, which are the foundation of the modern SI and central to the work of NMIs, illustrate this distinction well [6]. Maxwell provided an empirically based description of how unit systems facilitate unit conversion. In his approach, quantities are expressed as a product of factors: a numeric value and a symbol referring to a unit. Maxwell explained that the unit symbol can be thought of as a numeric variable, which is assigned a value according to the desired unit. For example, in the expression 19 m, 19 represents the value of a length measured in metres. To convert this to feet, one assigns $m = 3.28084$, the measure of one metre in feet, and evaluates the product

$$19 \times m = 19 \times 3.28084 = 62.33596 .$$

This explanation is grounded in empirical ideas, relying on the existence of reference physical quantities (units) and the measurement of relative amounts of quantities.

Nowadays, an abstract description of unit and quantity systems is more familiar. This treats the idea of *quantity* as fundamental: *quantity* is an abstract notion that is simply assumed [7]. Units are individual quantities that can be compared by ratio with other quantities of the same kind to obtain measures (numbers). Algebraic rules of *quantity calculus* can be applied to abstract quantities, enabling *quantity equations* to express relationships between quantities independently of any specific choice of units. These equations can be manipulated and analysed algebraically, providing a foundation for modelling physical systems. This view is grounded in abstract ideas, relying on a logical framework of mathematical concepts.

The distinction between the abstract and empirical concepts of quantity is important. It would be a mistake to assume that abstract ideas have simply replaced empiricism. Indeed, attempts to form a complete axiomatic description of unit systems based on abstract quantities have so far been unsuccessful. So the empirical explanation given

by Maxwell is still arguably more complete. De Courtenay explains how the meticulous quantification of measurement error (uncertainty) in metrology reconciles the inevitable discord between empirical data and abstract theoretical models [8]. Metrology spans the divide between these two domains. It is through measurement that we obtain information about the actual physical world, so metrology is inherently tied to an empirical world view. However, modern scientific language is formal, and so metrology must adapt to modes of expression that are universally understood. This necessity to align practice with common forms of expression is the one of the motivations for guidance documents like the GUM and the VIM [5, 4].

A sense of the difficulty in adapting empirical experience to abstract concepts is given in a remarkable account of Maxwell’s researcher assistants’ use of moving-coil instrumentation. In a private communication to Maxwell, reproduced by Schaffer, we read [9, page 36]:

“... we are now going ahead with the comparison of coils, and several men are able to rig up the various combinations out of their own heads, now that they know by inspection the difference between a

$$\begin{aligned} \text{shove} &\propto \text{current} \\ \text{kick} &\propto \int \text{current } dt \\ \text{jerk} &\propto \int \int \text{current } dt \, dt \end{aligned}$$

I have just got a clear case of double jerk from zero to + and back to zero and stop there”.

The empirical representation here is striking, yet Schaffer notes that these men were learning to see effects in the laboratory as “instances of more general principles of changing current and field strength”—in other words, in abstract terms. He also says, in a remark particularly relevant to this study, that “The problem the Cavendish faced was defining and distributing this fragile notion of practice.”

The role of measurement in linking abstract theories and meaningful empirical observations received further attention in the mid-20th century. Stevens coined the ‘schemapiric principle’ to refer to the duality where empirical procedures generate data that is interpreted through the lens of abstract theoretical concepts [10]. In a handbook for experimental scientists, he emphasised the importance of conveying meaning through careful use of syntax and semantics when reporting observations [11]. These issues remain pertinent today, as digitalisation progresses.

Stevens also discussed something he called *pragmatics*, referring to how scientists respond to the use of formal symbolic expressions. He may have sought to highlight a human element in the abstract-empirical tussle, writing “... the paralytic terror instilled by those clever souls who can calculate in those who cannot is a problem in applied pragmatics” [11, page 4]. Indeed, some metrologists express

reluctance toward mathematical formalism, while theorists may be prone to dismissing experimental complexities as secondary. This tendency suggests a bias toward theoretical representations over experimental practice. However, as already emphasised, the empirical knowledge embedded within NMIs is of fundamental importance. The fact that it does not always lend itself to abstract expression must not be mistaken for a lack of value.

In summary, metrology occupies a unique position between empirical and abstract representations of knowledge. Metrologists themselves may not be aware of this distinction. Similarly, experts in digital technology—whose discipline is inherently focused on abstraction—are unlikely to recognise these differences. This lack of awareness could present challenges for communication.

IV TOWARDS SUCCESSFUL DIGITALISATION

Sections II and III outline challenges to digitalisation that stem from the social structure of metrological groups. Communities of practice, staffed with dedicated NMI scientists, will likely find themselves at odds with abstract thinkers intent on codifying their practices. Digitalisation, approached in these terms, risks becoming what might euphemistically be called ‘disruptive’—and unnecessarily arduous for all involved. Strong leadership from within metrology communities is essential. The approach to digitalisation must acknowledge the unique challenges faced by metrology and avoid viewing digitalisation as merely a case of ‘change management’.

A Terminology

To achieve the goals of digital transformation in science, standardisation of terminology is essential. Broad guidelines are available to produce ‘FAIR’ data (Findable, Accessible, Interoperable, and Reusable) [12, 13]. However, metrological CoPs may be operating with local empirically-based interpretations. So, strategies are needed to deal with this.

Issues related to codifying processes and knowledge are not unique to metrology; they arise in other sectors as well. So, the challenges to metrology are to some extent already familiar to IT professionals. In business settings, the role of *business analyst* is typically tasked with gathering, documenting and formalising detailed requirements for digitalisation projects. The analyst acts to bridge the gap between business needs, which are likely practice-based, and digital designs, which are abstractions. However, the challenge in metrology is of an entirely different scale. Harmonisation on a global level must ensure that scientific information can be shared and reused as widely as possible.

To address this, the metrology community should consider a role analogous to the business analyst, one that would facilitate the harmonisation of terminology and concepts embedded within CoPs. The activities of people in

this *broker* role (as described in section II) could negotiate changes to align with conventional abstract forms (our laboratory is exploring this by offering tuition in mathematical modelling to early-career metrologists—see below).

The metrology community should consider strategies for managing terminology. Neumann observed a large and specialised terminology in use—over 20,000 terms in just one large NMI [14]. She proposed ways that working vocabularies could be reduced in size by structuring them inside well-defined contexts. To support this, she introduced the concept of a dynamic controlled vocabulary, which actively manages terminology while preserving nuances of meaning across different contexts.

The challenge of managing terminology is not unique to metrology; it is a common issue in large IT development projects and the IT industry has also developed strategies to address it. For instance, the *Domain-Driven Design* process formalises domain-specific languages in projects [15]. This establishes working vocabularies that both domain experts and technical team members agree on. This domain-specific language is adopted throughout the project—in code as well as documentation—improving communication and creating more meaningful and accurate work products. The idea sounds quite similar to Neumann’s dynamic vocabularies. Are these ideas that could be exploited more widely in metrology?

B Modelling

Digitalisation in metrology requires the development of suitable models. Modelling is a process of abstracting and representing knowledge in a way that can be codified as tangible artefacts. Whether in the form of written procedures, data structures, mathematical formulations, or software, reified artefacts are based on an underlying model representing relevant aspects of the domain.

However, CoPs may reify models locally that diverge from more widely understood formal representations. A striking example of this is described in the report of an international measurement comparison of microwave quantities [16]. The report states, on page 13, “We have the impression that many participants are not willing to completely disclose their method of uncertainty determination, which might be due to proprietary calibration techniques that are applied.” This situation led the pilot laboratory to abandon use of uncertainty data in the comparison analysis, as explained on page 15, “... it is questionable if the uncertainties would indeed represent the measurement capabilities of the laboratories and in this case it is better to abandon the uncertainties in the calculation of the [comparison reference value].”

The microwave metrology community has taken steps to address this issue. First, guidelines have been developed that describe the most common mathematical measurement models applicable to their tasks and explain how

to evaluate the corresponding uncertainties [17]. Second, software facilitating the use of these models in the laboratory is available [18], which enables metrologists to adopt standard models with little change to their laboratory practice. Could this type of response to the diversification of CoP artefacts be useful elsewhere?

The Measurement Standards Laboratory recently offered staff tutorials on the formulation of mathematical measurement models and the use of software for model evaluation. The initiative was well received, prompting the development of an e-Learning module to make these ideas more widely accessible. Tuition was deliberately offered to metrologists recruited within the last ten years, as their roles are still taking shape within CoPs. These metrologists are open to new ideas and can negotiate a place for those ideas in their groups.

V FINAL COMMENTS

The scientific knowledge held in NMIs is likely retained in a multitude of metrological CoPs, much of it embedded in empirical, practice-based forms. In contrast, external scientific communication and digitalisation efforts depend on abstract representations, which may not align with reifications developed by CoPs. As robust social structures with strong group identities, CoPs require careful consideration in any digital transformation. Abrupt change is neither realistic nor desirable, as it risks disrupting valuable knowledge and established practice. Effective transformation must actively involve CoP members and evolve through the continued negotiation of meaning within shared practice.

This article suggests several ways to influence CoPs, all of which involve members acting in peripheral roles—either as relative newcomers or as brokers who participate in multiple communities. A common theme in these approaches is that change is most effectively driven from within, by CoP members themselves.

ACKNOWLEDGEMENT

This work was funded by the New Zealand government. The author thanks Ellie Molloy for careful review of the manuscript.

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