



metrology



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The Silent Benefactor: Why Explaining the Importance of Metrology Involves Addressing the Counterfactual

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Abstract: Metrology, the science of measurement, is an essential underpinning technology—an infratechnology. The correct functioning of the international measurement system that metrology supports is a prerequisite for the development of technology and wider progress in science. Metrology and the measurement system are at risk of being underappreciated. They potentially face a ‘no-win’ environment: their consistent success, a testament to their effectiveness, ironically leads to invisibility. The public and media tend only to pay attention when things go wrong, resulting in negative headlines. Furthermore, metrology’s emphasis on gradual, incremental improvements, crucial for maintaining long-term stability and safety, is incompatible with the short-term focus of the media. This leaves metrology perpetually struggling to gain recognition for its vital contributions and can lead to a danger that metrology will not receive the recognition or resources that it needs to continue delivering benefits. A different way of explaining the indispensability of metrology is therefore needed. This work takes a novel approach to explaining the benefits of metrology by considering the counterfactual argument—examining the consequences if the international measurement system was to fail. It concludes that a balanced argument demonstrating what benefits metrology provides, challenged with the counterfactual of what would happen if it did not, is likely to be the most effective mechanism to ensure the work of metrology and the indispensability of the international measurement system are properly appreciated.

Keywords: counterfactual; impact; measurement system; metrology; national metrology institute



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1. Introduction

Measurement is ubiquitous, making everything function. From the GPS on our mobile phones, through healthcare and complex machinery, to weights and measures in the marketplace, all modern life depends on reliable measurement. And yet, the importance of measurement often goes unnoticed. This is because the measurement system on which we depend works so well. It is metrology, the science of measurement, that powers this measurement system and underpins the very fabric of modern society. It ensures the accuracy, consistency, and comparability of measurements across international trade, manufacturing, human health and safety, protection of the environment, global climate studies and scientific research; indeed, all human life [1] (similar structures also ensure reproducibility and transparency in the social sciences and humanities, but this article will concentrate on the natural sciences). However, effectively communicating the importance of metrology to a broad, or even a scientific, audience presents a unique challenge. Metrology is an infratechnology, an enabling technical infrastructure [2]. Imagine a well-maintained road network. Drivers rarely consider the engineering requirements that keep the road surface

smooth and the traffic flowing seamlessly. Similarly, the benefits of metrology are often taken for granted—it is like the road surface that enables the vehicles (or measurements) to pass smoothly. Drivers tend only to notice the road surface when potholes disrupt the flow of traffic or damage their vehicles. Similarly, inconsistencies in our measurement system would have a significant cascading effect, jeopardising scientific progress, technological advancement, and even public safety. Hence, it is the job of metrology to keep potholes off the measurement highway. The fact that we almost never notice issues with our global measurement system is an indication that it usually works seamlessly. This amazing ongoing achievement, paradoxically perhaps, causes much difficulty in communicating metrology's value, although authors from around the world have made attempts at solving this problem [3–7].

2. Discussion

2.1. *The Reason Metrology Works So Well*

When we refer to the global measurement system, this principally means the agreement on the International System of Units (the SI), the modern version of the metric system that first arose following the French Revolution at the end of the eighteenth century. The current SI, which was formalised in 1960, stemmed from the Metre Convention of 1875. This was an international treaty that formed an international organisation (IO) called the International Bureau of Weights and Measures (BIPM), and where member states agreed to act in common accord on units of measurement. BIPM is one of the oldest IOs still in existence and has grown in membership to cover over 98% of the world's economy. (The, often small, economies that are not members of the Metre Convention undoubtedly use the SI but, for a variety of reasons, often cost, are unable currently to join officially). At the core of the SI are, of course, the seven base units on which the system is based: second (symbol s, the unit of the quantity time), metre (m, length), kilogram (kg, mass), ampere (A, electric current), kelvin (K, thermodynamic temperature), mole (mol, amount of substance), and candela (cd, luminous intensity). Derived units are formed as products of the powers of the base units. Taken together, the base units, derived units and the 'defining' constants on which the base unit definitions rely provide all the units we need to make measurements in everyday life [8].

The values of these units are realised from their definitions by National Metrology Institutes (NMIs) all over the world as national primary measurement standards. These national primary measurement standards form the core of the infrastructure that then disseminates the values of these units to users via a structured series of measurement comparisons—often called a traceability chain. NMIs ensure their national primary standards are accurate and consistent by performing regular international comparisons of these primary realisations with each other. As a consequence, this ensures that calibrations received by users at the end of the traceability chain are also consistent. Hence, we can be sure that time is universal the world over, that radiation doses in the United Kingdom are the same as those in Canada, that car parts made in Japan will fit together perfectly with parts made in Germany, that a litre of milk sold in Brazil is the same volume as a litre of milk in Australia, and that a kilogram of potatoes in South Africa is the same mass as a kilogram of potatoes in China [9].

The stability and comparability of the system underpinning these activities—the global agreement on the size of units and the comparability of the realisation of their definition—continue almost unnoticed by those outside the metrology community. This is not least because of the intrinsic redundancy in the system: there is not simply one primary realisation of the definition for a given unit; many countries will maintain such a realisation, and traceability can be disseminated from any of these mutually recognised

primary realisations. Add to this that the realisations of the definitions of units at NMIs are usually of an uncertainty much less than that required by users taking their traceability from the NMIs, and this demonstrates the international measurement system's robustness by design.

So effective is the international measurement system that it is very difficult to find examples of when the system has let down its users. The most famous stories of 'measurement errors' actually relate to different issues. Some date from before our modern measurement system was agreed upon when different unit systems clashed, causing, for example, in the 1660s Rubens' cavasses to not fit the ceiling spaces in London's Banqueting House [10], in the 1620s the Swedish warship *Vasa* to be heavier on the port side [11], and in the early 19th century the satirist James Gillray to portray Napoleon Bonaparte as shorter than he actually was [12]. Other stories from modern times were caused when there was confusion between SI units and their conversion to local units by users, causing, for example, the Mars Climate Orbiter mission to fail in 1999, Air Canada Flight 143 to run out of fuel in 1983, and Tokyo Disneyland's Space Mountain roller coaster to derail in 2003 [13].

One example of the international measurement system coming close to not meeting the needs of users has been where the uncertainty with which unit definitions have been realised has approached the level of being insufficient for the needs of science and technology of the day. An example of this is the evolution of the definition of the metre. Originally this was defined as the length of a unique physical artefact—the length of a specific platinum–iridium bar, the International Prototype of the Metre. However, this physical artefact suffered from inherent limitations, not least because by 1960 it was not stable enough for the future needs of science, technology and industry. Recognising the requirement for a more accurate and accessible standard, the metre was redefined based on the wavelength of light emitted by krypton-86. This atomic standard offered improved accuracy and allowed for independent realisations in various locations. However, its reliance on a specific atomic transition and the purity of the krypton limited the uncertainty and stability of this definition. By 1983 this definition was once again in danger of not meeting the future requirements of contemporary users, and so the metre was redefined in terms of a fixed numerical value of the speed of light when expressed in the unit metre per second. Using a fundamental constant such as this to define a unit provided the ultimate reference point, as the most stable phenomenon known in nature. This approach also provided flexibility of realisation—any experiment involving the speed of light in its measurement equation could be used. The benefits of this change were clear, and thus for a long time metrologists have worked towards moving away from using unit definitions based on physical artefacts or material properties and instead basing all SI base units on 'defining' constants. This aim was finally realised on 20 May 2019, 144 years after the signing of the Metre Convention, when the kilogram, ampere, kelvin and mole were redefined and the definition of all the SI base units became dependent on fundamental (or conventional) constants [14]. (In fact, the second still relates to an atomic property, but since this is realised with accuracy many orders of magnitude better than any other base unit, this is immaterial). In this way the international measurement system had future-proofed itself and set up a virtuous circle whereby advances in technology could be realised directly as improvements in measurement, which provided the extra precision needed for advances in technology, and so on. In addition, the metrology community had removed the remaining structural weakness in the system—the potential for the uncertainty of the realisation of unit definitions not matching the requirements of end users.

2.2. *The Difficulty of Explaining the Benefits of Metrology*

The benefits of the SI are the stability, comparability and coherence that it provides. Stability allows confidence in determining trends over time, for instance, in environmental monitoring. Comparability allows measurements at different locations to be compared, for instance, ensuring machine parts manufactured across continents fit together perfectly. Coherence, a property unique to the SI, ensures that different measurements of the same quantity using different methods are comparable, and measurements of different quantities can be used together within the equations of chemistry and physics to add value, for instance in weather forecasting. The system as a whole also promotes continuous improvement, reducing the uncertainty of measurement gradually over time. These benefits are often taken for granted outside the metrology community because they are uninterrupted and universal—the system works, and continues to work, for its users.

The true value of metrology therefore lies in its infrastructural, cohesive nature. A vast amount of ongoing work, often unseen, goes into maintaining a stable, comparable and coherent measurement system enabling most of human progress. Herein lies the curse of metrology: its measure of success is stability, with incremental improvements over time. For the outside world, such endeavours seem less captivating and much harder to explain than the promise of the revolutionary breakthroughs of discovery science that aim to make progress by transformational step change. The latter clearly suits a news cycle that is inherently short-term, whereas the equally important story that the international measurement system continues to support daily life fails to make the news [3]. Stability and control, unfortunately, do not generate headlines. The most recent example of this was the 2019 revision of the SI, described above. Whilst this was one of the greatest modern stories of progress in science and multilateral international collaboration, which future-proofed our measurement system for decades to come, even this milestone proved more challenging to grab media attention than it should have been. While this revision marked a significant scientific achievement, the core message—everything has changed, yet nothing has changed—proved difficult to convey to the public and end users since they noticed no sudden or immediate difference in their lives or in the units they used [14]. To understand the real benefits of our global measurement system, therefore, we must explain the ‘counterfactual’—the consequences of a world without a robust measurement system.

2.3. *The Elusive Nature of Counterfactual Arguments*

Counterfactuals, by their very definition, reside in the realm of the hypothetical [15]. They explore the ‘what if’—the alternative path that would have been taken if a particular event had not occurred or if a different course of action had been taken. While such exercises can be intellectually stimulating, they pose significant challenges when used as the foundation for arguments. The primary difficulty lies in the inherent uncertainty of counterfactual scenarios. Since these events considered did not actually happen, empirical evidence is missing to support any conclusions drawn. Put another way—we cannot observe the direct consequences of the hypothetical alternative. This lack of empirical evidence makes it difficult to establish a robust link between the counterfactual and its supposed outcomes. Furthermore, counterfactual arguments often rely on a chain of assumptions, each of which introduces further uncertainty and conjecture. As the chain of assumptions grows longer, the reliability of the argument diminishes. The subjective nature of counterfactual thinking may also present a significant challenge, leading to disagreements and making it difficult to reach a consensus on the validity of the argument. Different lines of argument may construct different counterfactuals for the same event, based on biases, beliefs, and experiences [16].

Despite these challenges, counterfactual thinking is known to play a crucial role in various fields. For instance, historians use it to understand the impact of key events and decisions. Economists use counterfactuals to evaluate the effectiveness of policy interventions [17]. Epidemiologists use counterfactuals to assess public health interventions [18]. Indeed, in everyday life, we constantly engage in counterfactual reasoning to learn from our mistakes and make better decisions in the future. In a similar way, metrology should be able to use counterfactual thinking as a valuable tool for analysis of its benefits, not least because there are some advantages over counterfactual arguments in, say, history. Counterfactuals in history really are just that. There is no possibility of a real alternative—the counterfactual never happened. With metrology and the global measurement system, there is the possibility that the counterfactual could happen, even if we have no obvious examples, and this makes the thought experiment more practical, vivid and believable.

2.4. Virtuous Circle of Improved Measurement: A Foundation for Explaining the Counterfactual

It has been explained previously how metrology fosters a virtuous circle within our international measurement system. Improved measurement techniques lead to scientific breakthroughs, which in turn drive technological advancements that necessitate even more precise measurement. This continuous cycle of improvement underpins progress across various fields. Effectively communicating the importance of metrology requires a shift in perspective. Metrology's true value lies not in singular breakthroughs but in the silent, unwavering support it provides for scientific progress, technological innovation, and a well-functioning global society. By revealing and emphasising this virtuous circle and the substantial disbenefits we would see if it did not exist, we can start to see what metrology and the global measurement infrastructure continually deliver to society. This attempts to use counterfactual thinking as a scientific method—still a relatively new approach [12]. Without metrology and the stability and comparability of the global measurement infrastructure, the following would occur:

- Trade and industry would be significantly less effective and efficient, increasing waste, cost and the likelihood of critical failures in the supply chain and in the safety of products;
- Research, development and innovation in emerging fields would become slower, more costly and deliver less robust outputs, affecting the overall confidence and trust in the outcomes of science and the views of experts, and also having a significant negative effect in the 'reproducibility of science' debate;
- The evolving climate would not be properly understood, undermining the decision-making required to reverse or mitigate the negative effects of climate change;
- Evidence based policy decisions and impact assessment would become much harder and result in weaker conclusions, leading to slow or poor decision-making by authorities;
- Progress in science, growth of economies, improvement in living standards, technological developments in society and enhancement of quality of life would all slow down or even stop.

We could also list more direct, tangible examples of these general points—even more relevant for the general public—such as GPS systems giving the wrong location on smartphones; vehicles breaking down more often; more time taken for airport security checks, increased accidents due to mechanical failure; lower disease survival rates because of less effective healthcare; increased impacts from climate change; incorrect energy bills; unclear labelling of products; less choice in consumer goods; unclear value for money because of reduced confidence in weights and measures; poor economic growth and increased prices. The list could go on for some time!

This counterfactual approach is useful for explaining the benefits of metrology as an infratechnology because it tries to state what would happen if metrology did not maintain the international measurement system. It is particularly effective because it:

- Clarifies the impact of metrology by illustrating the benefits that would be lost without precise measurements;
- Makes the invisible visible: by bringing to light metrology's role as a silent benefactor that keeps everything working and continuously improving;
- Demonstrates metrology's social, economic and scientific reach: highlighting how the international measurement system is vital to everyday life, thriving industry, policy development and regulatory structures, and technological progress;
- Highlights the underpinning role of metrology in ensuring healthy and safe environments;
- Acts as an education tool to reveal the often hidden world of metrology to scientists, government, industry and the general public.

Furthermore, whilst case studies of systematic failures in the global measurement system to quantify these disbenefits are not readily available, several detailed investigations and case studies do exist about the positive economic benefits of metrology interventions and the measurement infrastructure [19,20]. The virtuous cycle, facilitated and driven by metrology, where improved measurement leads to scientific breakthroughs, which in turn drives technological advancements, is especially important in this respect since many modern theories of economic growth are predicated on technological progress [21].

At a minimum, we may assume that a breakdown of the global measurement system would lose these benefits and probably a lot more besides. This consideration is a reminder of the danger that counterfactual scenarios can dramatise risks and rely too much on engagement through fear. Whilst there is an argument that humans are often more motivated by potential loss than by potential gain, and thus illustrating what we stand to lose without metrology can engage audiences more effectively than listing benefits, this approach will not work alone. The counterfactual is an important tool in explaining the value of metrology, but it must be used as a counterbalance to a description of how metrology **does** work, is working, and has worked for decades to deliver the virtuous circle of continuous improvement. The corollary is, therefore, that all of these benefits would be taken away if metrology did not exist. An additional aspect of these benefits is that the maintenance, development and improvement of the global measurement system necessarily require international multilateral cooperation and consensus building through dialogue and compromise, even during political eras when these qualities are less fashionable.

3. Conclusions

The objective of this piece has been to highlight the fundamental yet often overlooked importance of metrology—the science of measurement—in supporting modern life and enabling scientific, industrial, and societal functions. The article has explained why metrology is essential, why its benefits are taken for granted, and why effectively communicating its value to both scientific and general audiences is challenging. It has then been proposed that highlighting counterfactual arguments is an important but rarely explored mechanism to demonstrate the importance of metrology. The benefits of this approach that this work has concluded are summarised below.

In a competitive world demand often outstrips the available resources. Infratechnologies, such as metrology and the NMIs that maintain the global measurement system, often find it difficult to compete in such environments. This is because, like other societal infrastructure (such as the road network), they are essential for modern life, and yet their immense benefits are taken for granted. They continue to work and deliver benefits

day after day, the measure of their success being stability and incremental improvement. When set against other requirements for resources that target (but do not always deliver) breakthroughs or disruptive change, infratechnologies may lose out—partly as a result of being seen to work so well and partly because they are often seen as less glamorous. Of course this is not the case. Metrology, NMIs and the global measurement system are more important than anything else because they are the fundamental building blocks of science and technology. Without the foundations they provide, there would be no discovery science, breakthroughs or disruptive change.

In this respect, we must ensure metrology and the measurement infrastructure are properly funded and maintained first, before considering anything else. This is because all other scientific progress relies on metrology maintaining the global measurement infrastructure. Metrology is an essential requirement for all other sciences. In order to communicate this message in an increasingly short-term media cycle, it seems that metrology must make the argument based on the counterfactual. By focusing on what would be lost or risked without metrology, we can make a more compelling case for its importance, making the abstract and often invisible benefits of metrology as an infratechnology both tangible and urgent. Performing this together with a presentation of the benefits of properly resourced NMIs and a robust global measurement system—to avoid a counterfactual-only narrative appearing too alarming—presents a forceful argument and brings metrology, the silent benefactor, to the fore. The efforts of metrology and metrologists in maintaining the global measurement system are akin to the graceful movements of a swan gliding effortlessly across the water. Beneath the surface lies a tremendous amount of unseen work to maintain, develop and improve the global measurement system, ensuring it remains robust enough to accommodate the current demands of science and technology and flexible enough to adapt to any future requirements. Taking the time and effort to explain the counterfactual is an essential tool to ensure metrology's importance is properly understood.

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