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Review Article

Deficiency of Metrology Education- How do we Solve the Problem?

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Abstract

Metrology which is the science of measurement and its application is a natural and vital part of our everyday life. It is a practical profession, vital for industry development, commerce, trade and regulation. However, despite the immeasurable scientific, technical, economic and social significance of metrology, it is generally unrecognised in educational courses. Most curricula in scientific, medical or engineering fields don't even mention the subject. This paper considers with keen interest, the drawbacks to metrology education, with the aim of promoting university awareness of the importance of metrology topics and the necessity for it to be introduced into university level academic curricula. The paper is keen to support academic institutions in developing metrology program curriculum in universities. To demonstrate the necessity of metrology education, this paper examines its significance and the consequence of it being undervalued in science, engineering and medicine. The paper formulates elementary metrological topics which should at least be part of university academic curricula.

Keywords: *Metrology; Education; University; Physics; Engineering; Chemistry; Biology; Medicine*

Introduction

Metrology which is a natural and vital part of our everyday life presents a seemingly calm surface covering depths of knowledge that are familiar only to a few. Metrology which is the science of measurement and its application [1] is practised almost every day, often unknowingly, in our day-to-day tasks. We find it almost impossible to describe anything without the need of metrology: Hours of sunshine, chest measurements, alcohol percentages, weights of letters, room temperatures, tyre pressures... and so on. Coffee and planks of wood are both bought by weight or size; water, electricity and heat are metered, and that affects our private economies. Bathroom scales affect our humour - as do police speed traps and possible financial consequences. In short, without metrology, today's life is barely conceivable.

Metrology is not just of interest to a very small number of specialized scientists; it is a practical profession, vital for industry development, commerce, trade and regulation. It ensures a stable, prosperous society and to the economic growth of nations [2]. However, despite the enormous benefits of metrology, educational activities concerning metrology are rudimentary and even keep declining [3]. Well-structured curricula about metrology and consistent textbooks for educational purposes are generally missing [3]. Considering the nature, role and importance of metrology in industry, trade, sustainability and legal matters [4], it is in itself a subject that needs to be incorporated in the curricula of schools, technical colleges and universities - and this is evidently not recognized in education programmes around the world. Many years ago, the George Washington University partnered with the National Bureau of Standards (now the National Institute of Standards and Technology or NIST) to offer graduate programs in metrology, but today, such programs are no longer available [5]. The International Committee for Weights and Measures [6] revealed that in many countries, there is inadequate provision for teaching in metrology at every level of the educational system: schools, technical colleges and universities. Metrology often has to be "learned on the job". According to Ibrahim, Bills and Allport [7], over 92% of the developing countries have no single institution that offers metrology courses.

Students at all school levels can benefit from the understanding of basic concepts of metrology and increased familiarity with such concepts would, in the long term, contribute to sound metrology system development, dissemination and use. Universities have the maximum potential for interaction with the metrology world; because they are the ultimate bridge between younger generations and professions and, at the same times, they are key producers of knowledge - important and often indispensable for national development. Thus, this paper recognizes the fundamental contribution metrology education can give to national developments if embedded in educational institutions most especially in universities. This paper focusses on universities, although, it relevant to other institutions of higher education.

The paper considers with particular interest, metrology education impediments and examines what we need to do with the aim of bridging the gap and to support academic institutions in developing the metrology program curriculum in universities. Some background and misconceptions about metrology that has motivated this work are presented in Section 2 and 3.

Metrology in educational institutions academic curricula – Why?

Undoubtedly, students of universities, technical colleges and other institutions of higher learning, are the potential managers and professional experts of the future.

Metrological principles apply to every measurement and observation made in every lab anywhere on the planet. As noted physicist Lord Kelvin said over a century ago, "…if science is measurement, then without metrology, there can be no science" [8]. Metrology is multi-disciplinary and allows measurements of all quantities to be linked to one another in a true and absolute sense.

Measurement is the indispensable tool by which humans define the world and reason about it. Astronomers patiently measure the dim light from distant stars in order to determine their age; Geologists measure shock waves when the gigantic forces behind earthquakes make themselves felt; The pilot carefully observes his altitude, course, fuel consumption and speed; The food inspectorate measures bacteria content; Maritime authorities measure buoyancy; Companies purchase raw materials by weights and measures, and specify their products using the same units. The availability of measuring equipment and the ability to use it effectively is essential if scientists are to be able to objectively document the results they achieve. Processes are regulated and alarms are set off because of measurements. Systematic measurement with known degrees of uncertainty is one of the foundations of industrial quality control and, generally speaking, in most modern industries the costs bound up in taking measurements constitute 10 - 15% of production costs. Good measurements can however significantly increase the value, effectiveness and quality of a product [9].

Metrology - the science of measurement - is undoubtedly the oldest science in the world and knowledge of how it is applied is a fundamental necessity in practically all science-based professions. "If measurements are faulty, analyses and interpretations based on these measurements are basically and irreparably fallacious" [10]. Thus, given a basic understanding of metrology (the science of measurement), even a non-scientist can begin to take part in a critical analysis of scientific claims across a broad spectrum based on metrological principles [10]. In fact, any nations with the prospect to develop must have established metrology education systems which include training centres, specialized educational institutions and formal metrology education at technical schools and/or university level [11].

Unfortunately, the general lack of knowing the term "Metrology" causes it to be a hard sell for institutions seeking to bolster it up [12].

Metrology in university academic curricula is essential

Metrology (the science of measurement) is important for scientific research, industry and our everyday lives, as the demand for measurements with high accuracies and low uncertainties continues to increase. It is now recognised that metrology provides a fundamental basis not only for the physical sciences and engineering but also for chemistry, the biological sciences and related areas such the medicine and the law.

Metrology in medicine

Health is an especially sensitive field. The measurements here are absolutely different from other metrological areas. The measurement object is a human. Every "measurand" is different. Measurements in this field are variable due to unrepeatability of measurements, so the need for more reliable measurement is critical. Thus, metrology is one of the most important and critical issues that need to be considered when defining the academic curriculum in medicine.

For the medical device industry and applications in the health sector, nothing is more important than patient safety. Hence, calibration and verifications of bio-medical equipment are vital in realizing quality control of the highest standard in medical equipment, and also in aiding the attainment of higher accuracy in diagnosis and effectiveness in treatment [13]. For example, a sphygmomanometer or thermometer that is not appropriately verified perhaps may lead to erroneous diagnosis and wrong medication [10]. Instances of blood sugar measurement errors presented by researchers of NIST reveal measurements accuracy significance showing in figure 1 [14].

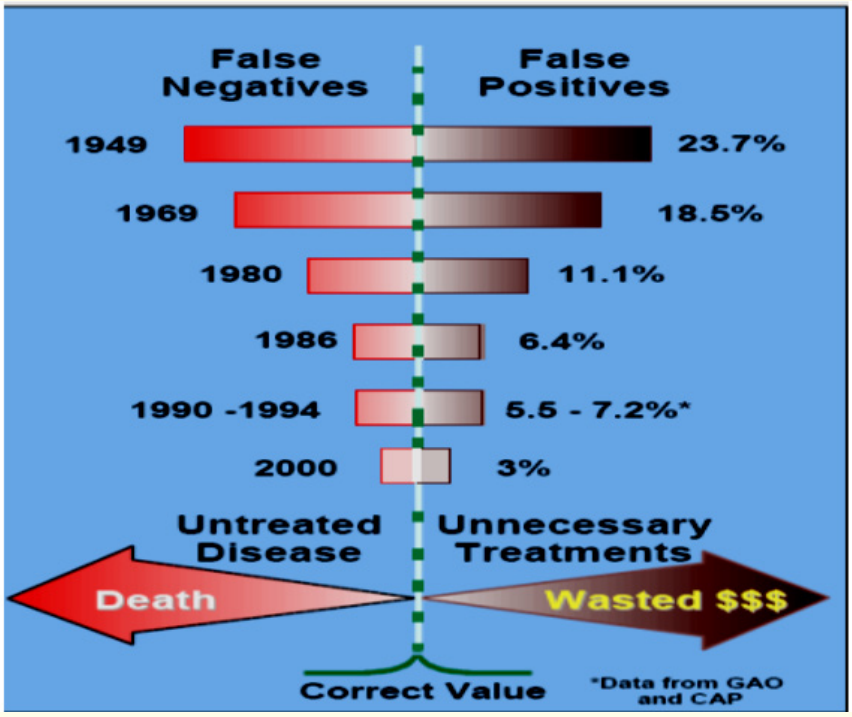

Figure 1: *Importance of accuracy in blood sugar measurement [13,14].*

If the measured blood sugar exceeds its true value, the medical doctor prescribes drugs, or if the measured blood sugar is below its true value, treatment will not be planned. In both cases, the patient will either face the risk of injury/death or will consume unneeded drugs and waste money [14].

Public Health is among the issues of considerable concern by the public in this 21st century.

Any qualitative research of questions such as; contents of specific substances in the human serum, rate of exposure of patients in brachytherapy or radiotherapy, detection of early biomarkers for cancer detection, bio-hazardous substances or toxins concentration in food, water or air, entails some measurements. The number of active substances in medicine, blood sample measurements, and the effect of the surgeon's laser must also be precise if patients' health is not to be jeopardised. Metrology application is needed to guarantee measurement reliability and traceability all through to international levels [15].

Metrology's link to medicine has not been recognised as much when compared to measurement needs in the medical field. The needs in this field are far from being met. The study of Karaböce, Gülmez, Akgöz, Kaykısızlı, Yalçınkaya and Dorosinskiy [13] reflected that medical devices that are essential to be calibrated against national or international standards by accredited laboratories are, however, undergoing improper calibration procedures. Mere checking of the device buttons, switches, numbers, lamps/LEDs, and displays are regarded as test or calibration. Some calibration certificates and labels were found to even being prepared without performing any measurement or calibration of medical devices [13]. The most worrisome according to the study of Karaböce, Gülmez, Akgöz Kaykısızlı, Yalçınkaya and Dorosinskiy [13] is that even most medical device users do not know the meaning of calibration and metrology. The crucial issue turns out to be to include metrology in the academic curriculum of medicine. This will educate and train medical people who are engaged in the use of medical devices and measurements and make them aware of metrological terms, the importance and role of metrology, the methodology of measurement and calibration and the effect of this in their field of work.

Metrology in chemistry and biology

Metrology is the science of measurements. While this expression has been utilized traditionally in relation with measurements of physical parameters (e.g. dimensions, pressure, temperature, time, etc.), there is no account why it should not be applied to measurements of biological (aerobiological or microbiological counts), chemical (identification/quantification of analytes) or physico-chemical (reaction rates, equilibrium constants, etc.) parameters [16].

Analytical Chemistry is one of the fundamentals of chemistry besides theory and synthesis, and it is at the helm of chemical measurement, therefore it requires the knowledge of chemical metrology. According to the European Commission [16], this basic approach has frequently been forgotten by analytical chemists. Perhaps, this is one of the main reasons for its being underrated in the past. Dealing with Metrology is one of the chief means of placing Analytical Chemistry in its rightful place. Metrology is an outstanding practical way of improving the quality of analytical information [16]. This is vital to aid analysts working at chemical or biological laboratories to establish pathways and tools in an effective way in pursuit of practical traceability in these fields Therefore incorporating metrology into the academic curriculum of Chemistry and Biology is a brilliant practical way of boosting the quality of analytical information of both the analysts and the end-users [16].

With the needs of quality products, growing technology, the economic contest, the request for improved living conditions, etc., the requirements of analytical requests are changing rapidly. Analytical sciences have to answer to these ultimatums and give genuine answers to the demands and not only results or data. Furthermore, it is essential that measurements are produced within an organised system which guaranties that [16]:

- Analytical results are stated within an accepted system of units;
- Results are comparable both over time and between laboratories;
- Results are given to the end-user together with information on their significance ("confidence limits" or uncertainty),

Thus, metrological knowledge is essential to the analytical scientist to be able to adapt to the growing demands. Introducing metrology into chemistry will help the future leaders (students) understand in a practical way some key concepts such as traceability, uncertainty, calibration, validation, etc., which are relevant to chemical and biological laboratories.

Similarly, the biological sciences have felt an unexpected technological revolution during the last decades, noticeable by the development of new analysis techniques based on gene sequences and functions. These tests are expected to be fast, efficient, and reproducible, to make a rapid accurate diagnosis and therefore appropriate treatment. Hence the importance of metrology in certification and accreditation systems for laboratories specialized in biomedical analysis [15].

Measurements of different kinds are carried out in analytical and bioanalytical chemistry [17]. There is no doubt that quality of chemical and biological measurements is an important issue in modern society, influencing the quality of life, thus the chemist and biologist should adopt metrology as part of their own discipline, rather than as a separate topic.

It is therefore essential to link Metrology in Chemistry and Biology in educational institutions curricula.

Metrology in physics and engineering

Although metrological methods are well recognized in the fields of Physics and Engineering in developed countries, in many domains (such as optical and pressure measurements, dimensional metrology, electrical measurements, time and frequency) the requirement for accuracy has increased by a factor of ten every ten to twenty years for the last fifty years. This trend has not stopped; on the contrary, it has accelerated as asserted in [6], this is the situation for time and frequency standards, which are the basis of space navigation and positioning systems. A different instance is the extremely stringent need for dimensional and mechanical metrology when subsystems designed for assembly are built in different factories, often in different countries, so as to guarantee the interfaces [6].

While metrology links in physics and engineering have been well recognized in developed countries, the reverse is the case in developing countries. Instances of knowledge of general metrology, flow metrology and legal metrology knowledge conducted in Nigeria presented by researchers [7] shown in figure 2 demonstrate that even engineering students totally lack understanding of the concepts of metrology.

Thus, the incorporation of metrology into physics and engineering academic curricula in universities will aid the formation of young persons to contribute efficiently to the design, realisation and support of sustainable projects with a scientific and/or technological content, for the benefit of the fast-evolving modern society. The programmes will help the students to become "critical, conscious and engaged engineering scientists in a spirit of liberal examination from a non-dogmatic and pluralistic vision towards society and the chosen engineering specialisation field, with emphasis on the sustainability of the solutions, ethics and awareness of the implications to the environment" [18].

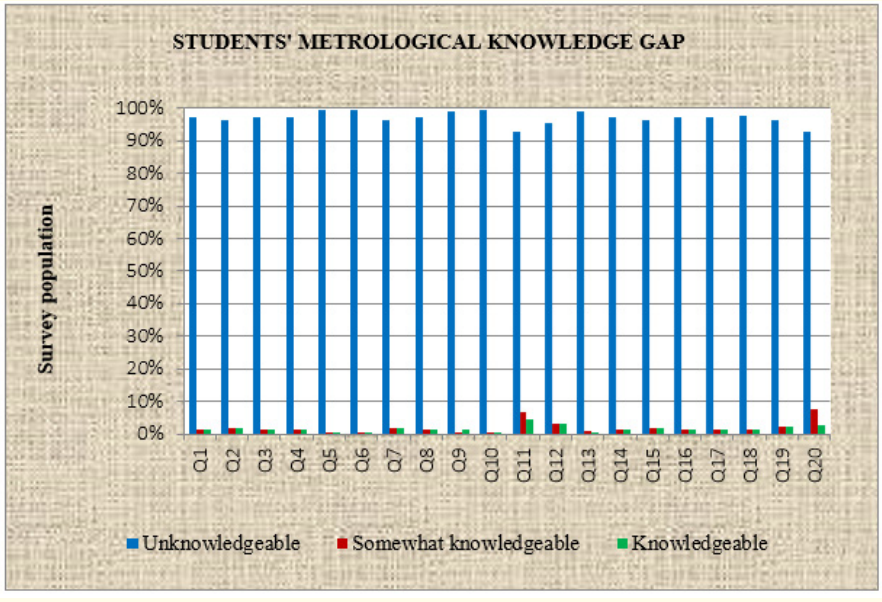

Figure 2: *Metrological Knowledge gap of the students [7].*

Metrology in statistics

Metrology is at present an unrecognized topic in statistics courses [19]. According to Castleton, Beyler, Genschel and Wilson [20], it is unprejudiced to state that the greater parts of students are unfamiliar with the idea of measurement error. A broad study conducted by Séré, Journeaux and Larcher [21] in exploring students' knowledge in getting measurements in the context of optics and electricity showed in the discoveries that, students often do not see a need for repeated measurements, and moreover, they did not generally being able to

distinguish between random and systematic error in data and frequently did not fully understand the objective of constructing confidence intervals. Instances of misunderstandings and misconceptions of measurement uncertainty (one of the key elements of metrology topics) among students based on the study of Lubben and Millar [22] are:

- "Measure once and this is the right value (sic)"
- "Unless you get a value different from what you expect, a measurement is correct (sic)"
- "Make a few trial measurements for practice, then take the measurement you want (sic)"
- "Repeat measurements till you get a recurring value. This is the correct measurement (sic)"
- "You need to take a mean of different measurements. Slightly vary the conditions to avoid getting the same results (sic)"
- "Take a mean of several measurements to take care of variation due to imprecise measuring. Quality of the results can be judged only by authority source (sic)"
- "Take a mean of several measurements. The spread of all the measurements indicates the quality of the Result (sic)"
- "The consistency of the set of measurements can be judged and anomalous (sic)".

Hence, metrology is an important topic that needed consideration in statistics courses. Familiarizing students to metrology concepts such as measurement error and measurement variability will assist the students in developing an understanding of the concept of variability in data and to illustrate how variation is at the heart of statistical reasoning and critical thinking. And, if students developed the knowledge of the existence of measurement variability, they have met one of the basic ideologies of comprehending variation: the veracity of variation in all data [20].

Introduce metrology into universities academic curriculum - Recommended topics

The following metrology academic curriculum aims at the formation of young persons able to contribute efficiently to the realisation and support of sustainable projects within a scientific and/or technological context for the benefit of the fast evolving modern society. Introducing it into the curriculum implies that a student should be able to follow an academic educational program to guarantee measurement consistency and traceability at both national and international levels. An important task in introductory metrology courses is to help students develop an understanding of the concept of metrology.

Metrology is separated into three categories with different levels of complexity and accuracy: Scientific metrology deals with the organisation and development of measurement standards and with their maintenance (highest level). Industrial metrology has to ensure the adequate functioning of measurement instruments used in industry, in production and testing processes, for ensuring quality of life for citizens and for academic research. Legal metrology is concerned with measurements where this influence the transparency of economic transactions, particularly where there is a requirement for legal verification of the measuring instrument.

The elementary metrological topics which should at least be part of university academic curricula are:

- Definition of metrology
- Objective of metrology
- Measurement's impact - some examples
- Metrology and quality assurance
- Measurement system/system of measurement
- Metrological units
- SI- The international system of units
- SI base units

- SI derived units
- Units outside the SI
- SI prefixes
- Writing of SI unit names and symbols
- Metrology vocabulary
- Information on metrology - links
- Categories of metrology
- Industrial and scientific metrology
- Measurement standards
- Certified reference materials
- Traceability and calibration
- Reference procedures
- Precision and accuracy.
- Accuracy and cost.
- Sources of errors.
- Concept of Repeatability, Reproducibility, Sensitivity, Readability and Reliability
- Measurement uncertainty
- Testing, verification, and inspection
- Legal metrology
- Legislation for measuring instruments
- Enforcement responsibilities
- Measurement and testing in legislation
- Metrological organisation
- International metrological infrastructure
- European metrological infrastructure
- Americas metrological infrastructure
- Asia Pacific metrological infrastructure
- African metrological infrastructure

Scientific, industrial and legal metrology knowledge must be promoted and developed in order to keep pace with the needs of, medical, industry, commerce, and society - and remain relevant and useful. At the end of their programme, the students should be able to

- Explain the significance of a measurement;
- Explain the benefits of metrology;
- Restate basic concepts and general terms of metrology;
- Explain and apply metrological units;
- Describe the basic calibration concepts and put it into practice;

- Explain the basic traceability concepts and put it into practice it;
- Distinguish between calibration, verification and inspection and put them into practice
- Differentiate between the concepts of repeatability, reproducibility, error, accuracy and uncertainty and put them into practice
- Describe measurements standards
- Analyse measurement uncertainties,
- Analyse and interpret results of measurements and put an end to the existing misconception that just measuring is enough.

No undergraduate course should go without these basic elements because the effects of this lack of knowledge already become apparent in advanced bachelor courses, during Master's level study and even in technical reports and papers. Admittedly, in most cases, the actual meaning can be deduced from the context, but nevertheless, it is wrong, and sometimes this carelessness may have serious consequences. Teachers have the duty to constantly alert students to such errors and stress the importance of accuracy with respect to reporting of experimental data. "What's learnt in the cradle lasts till the tomb".

Conclusion

This paper portrays the weakness of metrology education in the academic curriculum of universities. The review shows many students and users of measurement devices did not know even the term metrology. Considering the significance of metrology across the spectrum, a key issue is the need to introduce metrology into university studies.

The elementary metrological topics should at least be part of university academic curricula and no undergraduate course should go without these basic elements.

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