Measurement and instrumentation science and technology-the educational challenges

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Abstract. The paper presents in outline some of the major issues in education and training in measurement and instrumentation science and technology. Its aim is to initiate discussion and stimulate action. It considers measurement science in general education and in the formation of engineers and scientists.

1. Introduction
This symposium is devoted to the science of measurement and of the instrumentation by which it is implemented. It is the latest link in a chain of learned society activities concerned with this topic. These activities have contributed to the establishment, development and advancement of the science, through formal publication informal discussions and through social contacts and friendships among the scientists working in this field. It is the intention of the organisers of the present symposium that it should promote the progress of the discipline in this manner.

The present keynote address will endeavour to contribute to this progress by initiating and giving shape to a consideration of the educational aspect of the science of measurement and instrumentation, which deserves more attention than it has hitherto received.

The nature, scope, content and organisation of this science are now widely agreed, although it is continually changing and developing in response to the push of advancing technology and the pull of changing requirements. It provides a necessary basis for education and training, but is not of itself sufficient. It is therefore proposed to examine some of the educational challenges before us. [1, 2]

2. Requirements for measurement and instrumentation education and training
It would be desirable to begin by a detailed consideration of the place and importance of measurement and instrumentation in our world, to take a look at future trends and to examine the implication of this for education and training. The existing literature of fact and speculation about this is ample, but it is not adequately complete, organized or reliable to permit an adequate summary. Some general remarks must suffice.

It is proposed to distinguish two types of requirements. The first is the education and training of engineers and scientists. The other is the basic understanding of measurement required by all.

2.1. Engineers and scientists
Measurement is the essential and principal tool of natural science. Modern natural science, pure and applied, involves ever more diverse and complex measurements and often demands high performance
in respect of accuracy, dynamic response and the like. The life sciences have greatly increased their use of measurement. It is employed in the design, development, manufacture, operation and maintenance of all material goods. It follows that all natural scientists and engineers require a basic education and training in measurement.

Instrumentation is a key enabling technology of our civilization. It is, of course, the principal equipment by which measurement is performed. It is the essential component of many modern technical systems: control of processes, machinery, land vehicles, ships, airplanes, traffic control, weapons, security systems, medical diagnostic equipment to list only the principal ones.

We may distinguish different levels of expertise required in respect of instrumentation. There is basic competence required to use them, which is needed by all personnel. There is a level of expertise that may be termed ancillary, which is required of designers, implementers and technical managers of systems that have instrumentation of high functionality as an essential component. Finally there is the highest level of expertise, that required of the designers and developers of instrument systems.

Measurement is the basis of all trade and like transactions. Modern civilization demands effective units and standards of measurement, their establishment, development, maintenance and dissemination. Measurements must be performed with acceptable and clear statements of uncertainty. There is a demand for the assurance of quality, which often requires difficult measurement tasks. The growth of international trade means that the systems of measurement and of quality assurance must be international and must be implemented in all countries. The above tasks demand expert personnel educated and trained to create, operate and manage the measurement and quality assurance system. In addition a basic knowledge of the underlying principles of measurement and quality assurance is required of all involved in the manufacture and distribution of goods and related economic activities.

2.2. General education
The need of education in the principles of measurement is much more general than the formation of cadres discussed above.

The use of measurement is a fundamental aspect of modern civilization. We use measurement to investigate, describe and explain the natural world. We need some understanding of its principles to use effectively the technology on which our civilization relies.

From origins in the natural sciences the use of measurement has been extended to all domains of human thought, discourse and action. A few examples should suffice to indicate the universality and significance of its applications. It is extensively employed in psychology and sociology and related fields of study. It is the basis of much economics. It is widely applied in management.

An education and training in the principles of measurement is thus essential for everyone, starting from primary education, though secondary education and in many cases higher education and professional training.

This is commonly recognized and there is extensive teaching of measurement principles in general primary and secondary education and in higher education in those domains that make a significant use of measurement.

The development of measurement science as a discipline has not paid adequate attention to the wider use of measurement. It is increasingly recognised that the wide range and diverse applications of measurement are based on common logical and philosophical principles and share common problems. However the concepts, vocabularies and methodologies in the various fields of measurement in the literature tend to differ. The development of a unified science of measurement appropriate for all domains of application seems to be desirable. Such a unified measurement science would contribute to the meeting the needs of a better general education in measurement.

It may be remarked that the development of measurement science has not hitherto paid adequate attention to the needs of general primary and secondary education. This should be remedied.
3. Measurement science in the formation of engineers and scientists

Having recognized the central role that measurement should play in the general education of all humans it is proposed now to concentrate on engineers and natural scientists.

The development of measurement science has hitherto focused mainly on making it a teachable subject in initial professional education. It is proposed to take here a wider, holistic view and to consider all the processes by which a professional acquires competence and also to consider them not just as a professional, but as a whole person.

It is useful to employ the term professional formation to describe all the processes of education, training and experience that are involved in the fitting of a professional for his or her work.

Typically such formation begins with a period of initial professional education, which aims to equip the professional with the knowledge, attitudes and intellectual skills required. It is the basis of their professional competence. This initial professional education must satisfy certain general requirements.

The professional career of an engineer or scientist extends over a period of some four or five decades. During that time he or she will in general engage in many different kinds of task and have different roles.

The world is continually changing politically, economically, socially and culturally. The changes are significant and rapid. They cannot be reliably predicted.

The scientific and technical knowledge available is vast in quantity and diverse and complex in nature. It is growing and advancing rapidly.

An engineer or scientist can expect to work in the course of a professional career to work in very different worlds and with very different scientific and technical tools.

It follows from what has been said above that this initial professional education cannot be narrowly conceived as a preparation for first employment only, or to be training in the current state of the art. It must make the individual capable of learning and adapting throughout their career. It must therefore be based on generic transferable knowledge. In the case of measurement it must be founded on the concepts and principles of measurement science.

Such an education in abstract and general measurement science is, however, inadequate. It must be followed by initial professional training, which equips the professional to apply the abstract principles in practice.

Formation must continue throughout an engineering or scientific career. It should indeed extend throughout life including retirement.

When considering engineering and scientific formation it is important to bear in mind that the professional is not just an engineer or scientist alone. We must bear in mind that he or she has multiple other roles as an individual human being and as a member of society. Formation in measurement should be so devised as to develop the person in all respects.

4. Measurement science as an autonomous academic discipline

It has been argued above that all engineers and scientists require an initial professional education in measurement and instrumentation and that it must be based on measurement science. This presents the problem how measurement science can be incorporated in curricula and syllabuses.

Measurement science is a coherent systematic body of knowledge and can be effectively taught as subject. However, its concepts and principles are shared with other disciplines, particularly with those of systems, signals, information and control.

We must accept it therefore that, given the pressure that the vast amount of knowledge that must be imparted in an initial professional education in science and engineering, measurement science will often not be taught as an autonomous subject. Nevertheless the principles of measurement science need to be taught. It is not adequate to ensure that all the knowledge required for measurement is covered in other subjects. The teaching must be explicit, systematic and comprehensive. The devising of means of doing this is a major task before us.
It is a major obstacle to the teaching of measurement science that, if it is not taught as an autonomous academic discipline, there may be no centre or person in an institution engaged in the discipline and that the teaching of measurement will not be adequate.

5. Computer simulation in the teaching of measurement

Measurement science views measurement as an information process and measurement instruments as information machines. Many functions of modern instrumentation are realized by standard information hardware and software.

The principles of signal and information processing functions of instruments can most effectively be taught by computer simulation. This is certainly common practice. Commercial systems of hardware and software are widely available and are very effective.

Computer simulation can also be used to simulate the complete measurement system. The simulation can model the interaction of the measurement system with the system under observation and the relation between features of the physical embodiment of the system and its functions. Mostly this will be done with an idealized model of the physical embodiment, but realistic detailed models are also available for use. The use of such simulations in the teaching of measurement is an area for development.

Computer simulation has significant advantages of relatively low cost, power, flexibility, great convenience of use, flexibility and accuracy compared with laboratory experiments.

6. Laboratory teaching

Given the advantages of computer simulation, there is a distinct danger of too much teaching of the principles of measurement being delivered by this means. It is therefore necessary to stress that all teaching of measurement principles must have a significant component of laboratory work.

This requirement goes beyond the demonstration of phenomena and equipment by physical examples. Much of this can be accomplished by classroom demonstrations and modern visual aids.

An education in measurement principles must involve actual measurements, with demanding requirements, using actual measurement equipment. The use must give an understanding of the capabilities and limitations of the equipment. It must involve uncertainty estimation and the treatment of data.

Given the increasing use of mathematical models, it is important that laboratory work should illustrate the difference between theoretical models and reality. The comparison between theory and reality must involve analysis and explanation of the differences.

Having stressed the underlying principles, we shall return to laboratory teaching below.

7. Initial professional education in measurement for all engineers and natural scientists

It has been argued that all engineers and natural scientists should receive a basic education in measurement and instrumentation. Mostly they receive some education in the subject through laboratory work in their main discipline. This education is valuable, but is not sufficient for modern requirements. The education in measurement should be explicit, systematically organized and should cover adequately the main aspects of measurement science.

While a distinct course is desirable in all engineering and natural science curricula, it should nevertheless be possible to deliver a basic education in measurement through the usual laboratory work in any scientific discipline. This requires that the laboratory work be explicitly organized to teach the main principles of measurement.

Different disciplines involve very different laboratory work. The following examples must suffice to indicate the kind of laboratory tasks that should be possible in any discipline and would be suitable to teach some of the basic principles of measurement science.

The laboratory work should provide some tasks of measurement involving consideration of traceability to primary standards, with detailed uncertainty budgets and the like.
There should be adequate experiments to teach the dynamics of measurement including consideration of dynamic response of instrumentation and errors that may arise from it.

It is desirable that students be exposed to a variety of sensors, preferably with some problems relating sensor characteristics to its principle of operation and the main features of its physical embodiment.

Some experiments should involve measurement by system identification and parameter estimation.

In each case where a laboratory task is intended to inculcate an understanding of a principle of measurement science this must be explicitly explained and supported by adequate teaching material that links theory of measurement and instrumentation to the experimental task involved.

Ultimately, the aim of an education in measurement principles should not only make the professional competent to use measurement equipment and to interpret the results intelligently. It should give the professional some competence to devise a measurement system of moderate difficulty. The teaching of design of measurement systems requires more detailed consideration and will be considered separately.

8. Measurement and instrumentation design
The science of measurement and instrumentation is design orientated. Therefore all teaching of measurement principles should be directed towards an understanding of instrument and measurement system design. It is not possible to discuss this comprehensively within the scope of this address. The methods of doing it will depend on the curriculum and the place of measurement science within it. All that can be given here are some outline ideas.

Distinct courses in measurement science should usefully aim at providing an understanding of a formal model of the design process and its application to the design of measurement systems.

The teaching of sensor principles should be design orientated, with discussion of how the same function can be realized by different means, how the functional characteristics of the sensor depend on features of its physical embodiment and how this involves trade-offs in design.

In laboratory teaching of measurement science it is desirable to provide a design-build-and-test project, however simple. The difficulty of doing this is recognized. Laboratory work should involve some design analysis of the equipment used.

The teaching of measurement system design is an important area for exploration and discussion.

9. Education in measurement science of specialist professionals
Having considered some general aspects of the education of engineers and scientists in measurement science it is necessary to consider specialist professionals.

9.1. Professionals with ancillary level of expertise
The ancillary level of expertise in measurement science required in some disciplines such as control engineering is best provided by distinct courses in measurement and instrumentation. They should be delivered by lectures, problem classes, laboratory work and design tasks.

9.2. Professionals for the design of instruments and instrument systems
The design of instruments and instrument systems generally demands a team with a variety of expertise. The knowledge and skills required vary with the nature of the instrumentation. It may be suggested, however, that the best preparation for such work is a very broad initial professional education in applied physics or engineering science, with a thorough grounding in the general principles of measurement and instrumentation science which, if not part of initial education and training may be acquired as part of continuing professional development.

9.3. Professionals for measurement and quality assurance systems
Professionals who are engaged in the creation, dissemination, operation, and management of the measurement and quality assurance systems should ideally have received a good initial education and
training in measurement science. However, again, they may acquire the knowledge and skills in continuing professional development.

10. Initial professional training and continuing professional development
The development of measurement science has hitherto concentrated almost exclusively on initial professional education. As has been discussed above the, necessarily abstract and theoretical, knowledge acquired in that education must be completed by professional training.

There has been very little, if any, study or discussion of this vital component of formation. There is a need to study it scientifically, establishing the knowledge, skills and attitudes that such training should provide and studying methods of delivery of training. The study of the application of principles of measurement science in diverse practical environments may enhance measurement science.

A starting point should be the gathering of information about current training practice. Different formation systems have different ways of providing training. In some, training is integrated with education and takes place in educational institutions; in others it is a distinct stage of formation and takes place in industry and like environments. Well-established schemes of training have been in existence for many years. A critical review and analysis of present practice would be beneficial.

Practical training in medicine would seem to offer interesting examples. The training practice of armed services is also of interest.

Continuing professional development is an essential part of a professional career. It is a process that deserves more systematic study than it has received. A systematic review of existing practice is very desirable.

11. The formation of wider scientific and technical personnel
Discussions of the educational aspects of measurement science have hitherto focused mainly on education in universities and like institutions of the highest professional level of personnel. However, the educational and training needs of engineering and scientific personnel in measurement and instrumentation are much wider. There is a need in measurement and instrumentation for personnel to undertake work that is less theoretical and innovative and more concerned with existing practice. They require an adequate basis of measurement science for their work. The formation of such personnel would benefit from more thought and discussion.

12. Conclusions
It has been shown by the considerations above that there is extensive and important work to be done on educational aspects of measurement and instrumentation. If we do not respond to the challenge, who will? If we do not start now, then when?

References
[1] Finkelstein L 1994 Measurement 14 3-14.
[2] Finkelstein L 2009 Proceedings XIX IMEKO World Congress Lisbon 1070-5