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TEACHING MEASUREMENT THEORY IN METROLOGY, STANDARDIZATION AND CERTIFICATION

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Abstract – This paper describes some experiences in solving a difficult problem: organization of teaching General Measurement Theory in a situation where neither widely accepted opinion on its structure and contents nor authoritative textbooks and didactical materials exist. The contents of the discipline's theoretical part and exercises are given. The obligatory minimum of the theoretical part includes studying the initial mathematical concept like sets, binary relations, and mappings; formal logic and algebraic foundations of measurement as a cognitive process; features of measurement on quantitative and qualitative scales; formal models for measurands and procedures; and ways of mathematical description and estimation of measurement errors. Typical assignments are described. Features of the course instructional process organization are considered.

Keywords: measurement theory, teaching.

1. INTRODUCTION

In order to discuss teaching some discipline one can go in different ways.

So, approaches to the instructional process organization adopted in universities of various countries could be considered. The national specifics could be analysed aiming an elaboration of certain consensus on the discipline contents. An example of this can be found in [1]. However, it is too early to carry out such an analysis of Measurement Theory when extremely little engineering education curricula all over the world include similar courses.

Also, one could consider knowledge and skill requirements to the discipline from the view of students' future career and vocation as it was done, say, in [2] for information systems personnel. But the profession of "a person responsible for measurement" (cited by [3]) in the Western Countries is still in its early stage of shaping, and more or less profound and practically grounded needs would hardly be formulated. Eastern European Countries, including Russia, have lasting experience in educating measurement and instrumentation engineers, but in last decade the teachers there face problems of socio-economical nature some of which were highlighted in [4].

In the Tomsk Polytechnic University the department of Computer-aided Measurement Systems and Metrology teaches, since 1995, *bachelors* (four-year study), *engineers* (five-year study) and *masters* (six-year study) in educational direction 552200 – "Metrology, standardization and certification". Objects of these experts having a *technical* orientation professional activity are mainly as follows: methods and rules for setting norms on parameters of production, services and technological processes; technical specifications and documentation; systems of standardization; metrological assurance of scientific and industrial activity; methods and means of testing and quality control of production; systems for certification of production, goods and services; and systems of quality assurance.

In 2000 the Ministry of Education of the Russian Federation authorized a new state educational standard on the direction 552200, which has, for the first time, entered a new discipline titled "General Measurement Theory" into its curriculum. This discipline is called to replace one that in the previous versions of the educational standard referred to as "Theoretical Metrology" or "Mathematical Foundations of Measurement". One can see that the question is not about a simple change of the title, but about a transformation of the paradigm which underlies all the educational program.

The course is learned by students in the second semester of the second year and has a rather small size: 36 hours of lectures and 16 hours of practical work exercises. Also the course stipulates 52 hours of self-supporting students' study for stimulating their creative activity. During previous three semesters the students receive a usual volume of knowledge on a group of natural science disciplines, mathematics, in particular, probability theory, and informatics.

Table 1 shows a Bachelor of Engineering in Metrology, Standardization and Certification curricular structure. Here the bottom row corresponds to the first semester of study and the top row to the eighth semester.

Let us notice, that a problem of the organization of teaching of the Theory of Measurements is not simple in a situation where there is no standard opinion on its structure and contents (see, for example [5, 6, 7]), and where are also no authoritative textbooks and methodical materials. To give a certain solution to this problem is the point of issue below.

TABLE 1. Curricular structure for a Bachelor of Engineering in Metrology, Standardization, and Certification (552200)

Certification	Standardization Technology	Economics of Quality	System Analysis	Measurement Information Systems	Experiment Design II	Interchangeability			
Legal Issues	Sociology	Living Safety	Methods & Tools for Measurement, Test and Control II	Automation of Measurement, Test & Control	Qualimetry	Experiment Design I			
Economics	Methods & Tools for Measurement, Test & Control I	Industrial Management	Statistical Program Packages	Quality Systems	Microprocessors in Instrumentation				
Economic	Electronics	Metrology	Standardization	Statistical Quality Control	Digital Electronics	Practical Metrology	Standardization Systems		
English	Philosophy	Political Sciences	Ecology	Material Science	Intellectual Property	Physical Foundations of Measurement	General Measurement Theory	Theory of Signals & Circuits	Machine Parts
English	Electives	Higher Mathematics II	Physics III	General Electrical Engineering	Mechanics				
English	Culture	Chemistry	Higher Mathematics II	Physics II	Informatics I	Engineering Graphics II			
English	Fatherland's History	Higher Mathematics I	Physics I	Informatics I	Engineering Graphics I				

2. COURSE GOALS

This course plays an important part in the curriculum. It is an introductory course in all the technical career programs and has strongly a methodological, conceptual emphasis. The latter aspect allows to consider the discipline to be, in the future, a general education course for all university students.

As a result of teaching the discipline a student must learn main ideas inherent to measurement as one of general tools of human cognition, description and transformation of the real world. Namely, the student has *to know* the following:

- elements of the measurement process;
- measurement axioms and scales;
- procedures to measure physical and non-physical quantities;
- probabilistic nature of measurement errors; methods of mathematical description of and estimation of measurement uncertainty.

The student must be *skilled* in

- revealing measurement scales and methods which are suitable for the estimation of a given property;
- applying methods of measurement data processing which are adequate to the measurement scale and the data origin.

The course should be a basis for teaching further in such disciplines as Metrology, Qualimetry, Standardization, Quality Systems, etc. (see Table 1).

In the next section, we will give the course's theoretical part description divided into modules (shown in boxes) with relevant comments justifying a particular selection of topics studied in the appropriate module.

3. COURSE THEORETICAL PART CONTENTS

It is supposed that the theoretical part includes the following material.

Module 1: *Introduction*
Course goals and objectives. Course volume and structure. Required literature. Grading standards and criteria. Subject of the General Measurement Theory (GMT). Framework of the GMT. Short history of the GMT.

Comments: GMT is devoted to assigning numbers to objects. When composing the syllabus we adopted a representation approach to the study [8]. Our deep conviction is that this approach is most creative and fruitful and allows to unite measurements of both physical and non-physical quantities by means of a single formalism. In spite of that, from time to time, the approach is (frequently justly) criticized (see, for example, comparatively recent paper [9]), its main achievement is that it permits revision, deepening and extending of its concepts without a violation of the general idea: homomorphism of mapping of an empirical relational system to a numerical relational system.

The GMT framework can be conveniently described by the ordered quintuple presented in Fig. 1,

$$\left\{ \begin{array}{ccc} & \mathcal{B} & \\ \mathcal{A} & f & \mathbf{H} \\ & \mathcal{A}_r, & \end{array} \right\},$$

where $\mathcal{A}$ is an *empirical relational system* (object under measurement); $\mathcal{A}_r$ is a *reference subsystem* (that is a part of the empirical system of which some a priori information is given); $\mathcal{B}$ is a *numerical relational system*; $\mathbf{H}$ is a *subject* (that is a media of natural or artificial intellect, for an aim of which a measurement problem is being solved); f is a *set of rules* for mapping the empirical system into the numerical one [10, 11].

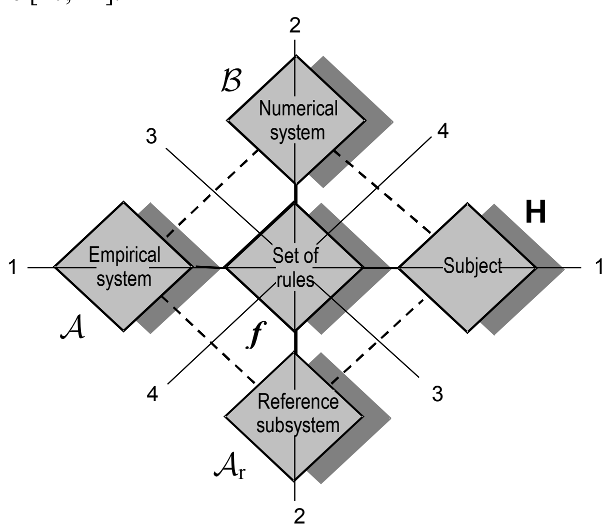

Fig. 1. Measurement model

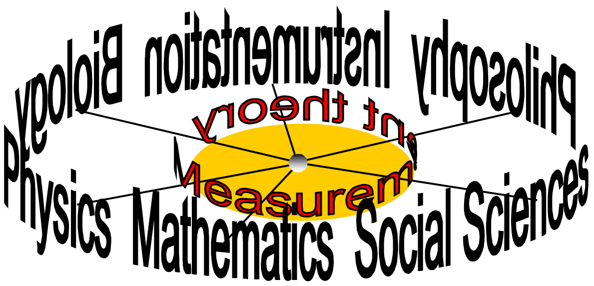

Fig. 2. Measurement theory is a focus of various sciences

Naturally, GMT is considered to be a focus of various disciplines (Fig. 2).

Module 2: *Initial mathematical concepts*

Sets. Operations over sets. Properties of operations over sets. Set of all subsets, covering and partitioning. Cartesian product of sets.

Binary relations. Graphic representation of binary relations. Matrix representation of binary relations. Main properties of binary relations. Equivalence relations. Order relations.

Correspondences. Mappings. Mapping representations. Mapping classes.

Comments: Knowledge of these concepts is necessary for the right understanding of main findings of GMT. Traditionally, a common engineering curricula do not include those what, in our view, is one of reasons why GMT has so little applicability in instrumentation.

The main attention here should be paid to such binary relation properties as reflexivity, irreflexivity, symmetry, antisymmetry, transitivity, linearity, and trichotomy. The module expounds the definitions and basic properties of equivalence and order relations. Related notions such as tolerances, quasiorders, partial, weak, and linear orders are introduced and discussed with a particular emphasis on their graphic and matrix representations (see, for example, Fig. 3, among the others, it shows that so many binary relations may exist over barely two-element set, namely, 2^{n^2}, where n is the set cardinality).

Module 3: *Physical quantity calculus*

Object, property, quantity, value, mathematical model.

Dimension of physical quantity. Quantity structure. Axioms. Homomorphism of quantity structures.

Equations between quantities. Dimensional analysis.

International System of Units.

Comments: This module introduces an algebra of quantities in a manner similar to what has been described in [12]. The concept of a physical quantity is introduced. It is demonstrated how a quantity structure may be constructed from given base elements, for example representing mass, length and time. Notions of isomorphism and homomorphism of a quantity structure, and corresponding axioms appear here first time in the discipline.

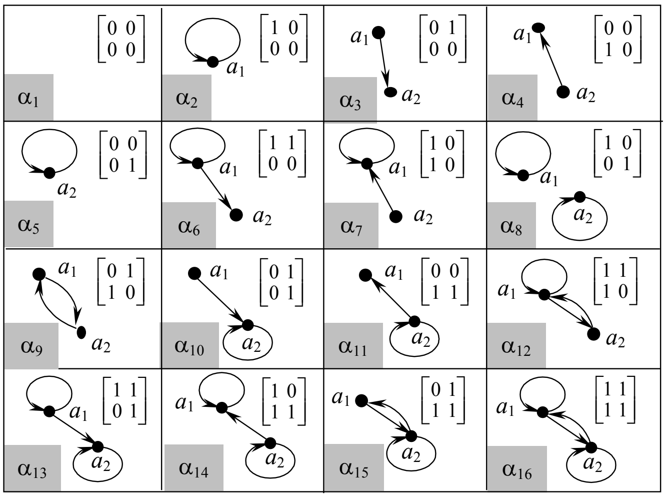

Fig. 3. Graphic and matrix representation of all binary relations over the two-element set

Quantity calculus constituted the basis for setting up the International System of Units [13, 14].

Module 4: *Measurement scales*

Definition of measurement. Measurement theory problems.

Measurement scales. Absolute scale. Ratio scale. Interval scale. Order scale. Nominal scale. Comparative scale characterization.

Comments: GMT includes three basic problems:

- *representation*, solving of which allows to justify a number (or symbol) assignment for the object under investigation;
- *uniqueness*, solving of which allows to know the degree to which the type of representation of chosen approaches are the only possible for the object under investigation; and
- *adequacy* (or uncertainty), solving of which allows to estimate the degree of trust to measurement result.

It is worth to note that S. Stevens' interpretation of scales (Fig. 4) is oversimplified. This is suitable for describing variable types in statistics but results in considerable lack of details in analysis of measurement procedures. So, if measurement results in nominal scales are class names or labels, then how are the classes themselves obtained? Classification of an object is an algorithmically difficult procedure. If a human intelligence realizes it quickly and, as a rule, faultlessly, then how to train, say, a robot to do the same?

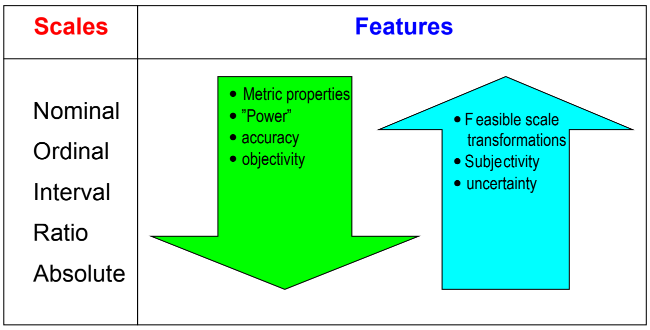

Fig. 4. Spectrum of measurement scales

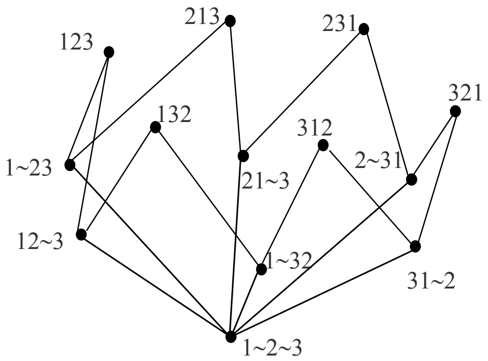

Fig. 5. All quasiorders over the three-element set

That is why, in series of traditional treatment of scales, this module includes other scale interpretation allowing the comparison of measurement results obtained in qualitative scales [11]. Fig. 5 shows this kind of possible ordinal scale.

Module 5: *Measurement procedures*
Mathematical description of measuring procedures and instruments. Discretization and quantization.
Procedures of quantitative measurement.
Procedures of qualitative measurement.
Control, diagnosis, recognition.

Comments: This module considers models of measurement procedures in different scales and their peculiarities [10]. It is interesting to note that some non-physical quantities can be measured just like physical ones, especially in economics [15].

Special attention is paid to procedures of control, diagnosis and recognition which are treated as nominal scale measurement.

Module 6: *Measurement errors*
Errors origins and classification. Formal description of errors. Error characteristics. Error and uncertainty.
Systematic error. Random error. Estimates of error characteristics. Properties of estimates. Measurement results processing.
Errors of qualitative measurements.

Comments:

The problem of errors and uncertainty is one of the central concerns of GMT. It seems to be very comfortable to introduce probabilistic nature of measurement errors on the same mathematical basis, that is, sets and relevant operations, as in Module 2.

Some difficulties exist with the consideration of uncertainty of qualitative measurement, though useful propositions to solve the problem can be found, for example, in [16, 17, 18].

4. COURSE PRACTICAL PART CONTENTS

The following topics for recitations and exercises are supposed to be useful: "Sets and operations over sets", "Binary relations and their properties", "Mappings", "Dimensional analysis", "Measurement scales", and "Measurement uncertainty processing".

Typical tasks of the topic devoted to sets are, for example, "to prove that $\varnothing \neq \{\varnothing\}$" or "to explain the Russel's paradox". Under the topic about binary relations students count how many equivalencies are over the given set and then determine them. It seems to be very useful that students solve puzzling logical problems on one-to-one correspondence. Dimensional analysis provides a wide possibility to train in structuring on practical examples of dimensional formulae and equations taken from different parts of physics and in forming "order of magnitude" estimates of certain properties of physical systems. Problems on measurement scales look like "to compare set of values {2, 3, 4} if they are obtained on ratio, interval and ordinal scales. What may they mean? What may you do with them? How can their uncertainty be estimated?".

To evaluate how well students have learned the topics they are required to go through two tests during the semester. There is a final exam on the course.

5. TEXTBOOK

At present, the first of the authors is finishing a work on a manuscript of a textbook titled "General Measurement Theory" which will, more or less, fill up a lack of the printed pedagogical material on the topic. The manuscript (Fig. 6) is supposed to be published by the state publishing house "Vysshaya Shkola" ("Higher School") in Moscow in 2003 and will be recommended by the Ministry of Higher Education of Russian Federation as a textbook for universities of technology in this country.

6. CONCLUSION

Our short teaching experience in the GMP on the version proposed above has so far shown that students meet little difficulties for learning the mathematical apparatus rather unusual to this field. They are very interested in the studies and become ready to creative perceiving of consequential special disciplines.

Fig. 6. The textbook cover

The work is surely continuing aiming to provide maximum valuable knowledge and skills for future students' vocation.

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