Measurement science in methodological instruction of Ph.D. students of technoscience

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Abstract. Technoscience is a result of integration of technology with empirical sciences, including not only physical sciences, but also life sciences, social sciences and cognitive sciences. The development of technoscience is unthinkable without measurement and mathematical modelling, being two interrelated operations used for acquisition and representation of knowledge. Measurement fundamentals must, therefore, belong to the core of methodological instruction of Ph.D. students of technoscience. This keynote speech will provide an outline of a graduate course on methodological aspects of technoscientific research, whose programme includes conceptual analysis of the dialectical relationship between measurement and mathematical modelling, of the role of measurement in scientific explanation, of the role of measurement in the context of discovery and in the context of justification, as well as of the role of measurement in mitigating uncertainty of scientific knowledge.

1. Introduction
Many today's research practitioners seem to share the famous opinion: "Philosophy of science is about as useful to scientists as ornithology is to birds", once expressed by the 1965 Nobel Prize winner, Richard P. Feynman [1]. They are usually not aware that on another occasion, in his famous paper "Cargo cult science", the latter complained about researchers who imitate research "rituals", i.e. carry out research activities in an apparently correct way, but without understanding their essence, and – consequently – without any chance for obtaining meaningful results and using them in a productive manner [2]. Does philosophy of science really matter for research practitioners? The following opinion on the significance and educational value of the history and philosophy of science – expressed in 1944 by another great physicist Albert Einstein – cannot be ignored: "... many people today – and even professional scientists – seem to me like somebody who has seen thousands of trees but has never seen a forest. Knowledge of the historic and philosophical background gives that kind of independence from prejudices […] from which most scientists are suffering. This independence created by philosophical insight is – in my opinion – the mark of distinction between a mere artisan or specialist and a real seeker after truth."[3] Paradoxically, those "artisans" are today quite systematically trained in their professional skills, while the candidates for the profession of the "seeker after truth", i.e. Ph.D. students, are not: the regular academic courses on philosophy of science and research methodology are rarely offered to the students of science and technology. Moreover, the vast majority of those courses are given by philosophers of science who, unsurprisingly, are inclined to ignore practical issues of research, as being
trivial, and to focus on abstract controversies, as being intellectually more attractive. Since research methodology is actually an interdisciplinary combining philosophy with science and technology, it would be very beneficial for research practitioners to follow the courses inspired by all those three sources of ideas. There is a need for a less sophisticated and more practical approach which does not focus on the overgrown terminology of philosophy of science – e.g. on classification of the panoply of stances promoted by various schools of thinking – but offers guidance in the everyday activities aimed at generation and evaluation of knowledge. On the other hand, it should be, however, avoided another extremity: the course on the philosophy of science and research methodology should not be replaced with a quick-reference guide for Ph.D. students in a desperate need to make their theses satisfy minimum formal requirements being in force in their domain of study…

2. Science, technology and technoscience

Science is usually understood as a systematic enterprise aimed at generating and organizing knowledge in the form of testable explanations and predictions about the natural world which comprises all the components of the physical universe (atoms, ecosystems, people, societies, galaxies, etc.), as well as the natural forces at work on those components. According to the Anglo-Saxon tradition, humanities do not count as sciences. So, the studies of various artefacts of human culture and various cultures themselves – philosophy and the studies of languages, literature, religion, arts, history, law, etc. – remain beyond science. The corresponding terms in some other European languages – e.g. Wissenschaft in German or nauka in Polish – have a broader meaning since they encompass all the academic disciplines, including humanities.

The sciences whose explicit goal is to generate knowledge and support understanding, regardless of potential applications, are called pure sciences or basic sciences. The sciences whose explicit goal is to solve practical problems, e.g. to develop new technologies, are called applied sciences. The boundary between pure and applied sciences is rather blurred: the research findings in pure sciences often have useful applications, and intentionally applied research may contribute to better understanding of the natural world. Applied sciences play today an important role as a bridge between pure sciences and technology usually understood as the fabrication, modification and usage of tools, machines, techniques or systems – aimed at solving practical problems or improving existing solutions to those problems. Science and technology frequently contribute to one another: scientific advances lead to the development of new technologies, and new technologies broaden the experimental potential of science, enabling advancement of research. This is a substantiation behind introduction of the concept of technoscience addressing the integration of science and technology, which has been progressing from the beginning of the 20th century (for more details see the recent book by the American philosopher and historian of science David F. Channel [4]).

3. Philosophy of science and research methodology

Philosophy of science is the study of assumptions, foundations and implications of science. Philosophy and science are often perceived as quite separate enterprises, seemingly having little to do with one another: philosophy is viewed as a search for answers to abstract questions, concerning such issues as meaning of life, while science is understood as a study of more down-to-earth matters. It turns out, however, that philosophy is omnipresent in science. There are not only philosophical problems concerning foundational concepts and tools used by scientists but also philosophical issues which are directly relevant to, and directly affect, the day-to-day work of scientists.

Almost until the end of the 20th century, the development of philosophy of science had been predominantly shaped by the advancement of physics (including astrophysics), especially by the research practices specific of that domain. Since the evolution of other scientific disciplines – in spite of the 19th-century prophecies and 20th-century endeavours – had not always followed the paradigms of physics, it has turned out at the end of the 20th-century that certain methodological guidelines of the philosophers of science did not match the reality of most dynamic fields, such as information sciences, life sciences and cognitive sciences. The philosophical discourse was, in particular, still focused on laws
and theories while for those sciences semantic, mathematical and computational models were more important. Today, an urgent need for accommodation of methodological follow-ups of this situation is generally recognised.

In English, two related although different meanings are associated with the term methodology: on the one hand, it is understood as the system of methods and principles used in a particular discipline of science or art; on the other – as the branch of philosophy concerned with the study of methods and procedures used in science (or in a philosophical system) [5]. In some languages, there is no such ambiguity because two different terms are associated with those two meanings, e.g. in Polish metodyka means the system of methods and principles, while metodologia is the name for the branch of philosophy, focused on the scientific method; a similar distinction exists in German [6]. To avoid ambiguity, the philosophical study of the scientific method is called in English philosophy of science and the system of methods and principles used in a particular discipline of science (or group of disciplines, such as empirical sciences) is referred to as research methods and research methodology. To avoid the necessity to enter into unnecessary distinctions, the combined term philosophy of science and research methodology will be used hereinafter.

4. Cornerstones of teaching philosophy of science and research methodology
The philosophy of science and research methodology is about so-called scientific method, i.e. the most general paradigm of doing scientific research, followed by Western civilisation systematically since the 17th century, and in some elements – since the times of Ancient Greece. Its naïve image, presented usually in the secondary schools, may be outlined as follows:
- An objective (i.e. impartial and unbiased) researcher makes observations and measurements concerning a selected object of study.
- On the basis of the results of observations and measurements, the researcher works out a theory which is able to explain those results and to enable prediction of the future states and behaviours of the object of study.
- On acquiring additional results of observations and measurements, which are not coherent with the already accepted theory, the researcher corrects this theory (possibly, in an iterative process).

An academic course, devoted to the philosophy of science and research methodology, must provide much more complete and precise description of the scientific method, as well as its critical analysis. This requires introduction of a number of highly abstract concepts (and related terms) which play an important role in research practice, in communication of research results and in scientific criticism. At first glance, this may seem a bit burdensome for the students trained on purely technoscientific literature, but they quickly discover the beneficial impact of this difficult experience when approaching more practical problems, especially those which require profound logical argumentation. As the British neuroscientist Rodrigo Q. Quiroga explained in his 2017 book [7], we not only think with concepts, but we also use them for remembering our external and internal experience. This enables us to both compress memorised data and make thinking more efficient. The famous statement “By giving the wrong name to an object, we are contributing to the misfortune of this world” [8] is pointing the essence of this problem.

The logical structure of the scientific method is the basis for structuring the contents of an academic course devoted to the philosophy of science and research methodology. The most typical and – in fact – indispensable components are the following issues: mathematical modelling and measurement, scientific explanation, generation of hypothesis (the so-called context of discovery), their transformation into scientific knowledge (the so-called context of justification) and uncertainty of scientific knowledge.

5. Measurement in teaching philosophy of science and research methodology
It follows from the rough outline of scientific method, provided in Section 4, that mature science is unthinkable without measurement. However, despite widespread recognition of the importance of measurement for research practice and technoscientific progress, the covering of metrological issues in the handbooks of the philosophy of science and research methodology is rather limited. The statistical
data provided in Table 1 seem to well corroborate this observation. They indicate that the philosophers of science are inclined to think about measurement as a source of uncertainty-free information…

**Table 1.** The numbers of occurrence of three key terms of measurement science in three recent handbooks of philosophy of science.

| Key term               | [9] 275 pages | [10] 425 pages | [11] 200 pages |
|------------------------|--------------|---------------|---------------|
| measurement            | 33           | 240           | 2             |
| measurement error      | 0            | 0             | 0             |
| measurement uncertainty| 0            | 0             | 0             |

The famous mathematician and polymath John von Neumann exaggerated, most probably, when saying: "The sciences do not try to explain, they hardly even try to interpret, they mainly make models"[12], and having in mind mathematical models. In this way, however, he made us aware of the crucial role of mathematical models in science. We realise the importance of mathematical modelling even more when getting aware that not only identification of mathematical models requires results of measurement but also any measurement method or technique requires several models to be identified, viz. the model of a system under measurement, the model of the measurand conversion into treatable signals and the model of the measurand reconstruction. A deeper analysis of the mutual interdependence of measurement and mathematical modelling is showing that the epistemic status of those two operations of vital significance for science is comparable and that evaluation of measurement uncertainty is necessary but not sufficient for evaluation of the uncertainty of scientific knowledge (cf. Chapters 5 and 6 of [13] for more details).

Measurement and mathematical modelling play a key role in scientific explanation. According to the Western intellectual tradition, to explain a phenomenon, an event or a process means: to remove perplexity, or to change the unknown to the known, or to identify causes of events or phenomena. According to the Greek philosopher of science Stathis Psillos, the explanation of a fact (explanandum) is achieved by stating some causal or nomological links between it and the facts that are called upon to do the explaining (explanans). There are two broad approaches to explanation. According to the first, explanations are argumentative: to explain an event is to construct such a line of argumentation that the explanandum follows – logically or with high probability – from certain universal or statistical laws and initial conditions. Most typical species of this genus are deductive-nomological schemes of scientific explanation. According to the second approach, an explanation needs not refer to any scientific law to be complete; it is enough that it specifies the relevant causal mechanisms [14]. Although not directly mentioned, measurement and mathematical modelling are parts of both approaches since both scientific laws and causal mechanisms have the form of mathematical models, and initial (or boundary) conditions must be defined on the basis of measurement results (cf. Chapter 7 of [13] for more details).

A fundamental distinction, emphasising a qualitative difference between two stages of scientific work, viz.: generation of hypotheses (in the context of discovery) and their transformation into theories or other pieces of scientific knowledge (in the context of justification), is usually attributed to the German philosopher of science Hans Reichenbach [15]. According to some interpretations, the context of discovery, unlike the context of justification, should be a subject of study belonging to psychology and sociology rather than to philosophy of science because the act of conceiving a new idea is not necessarily a rational process, and therefore cannot be regulated [16]. Alternative interpretations, however, stress the importance of the presence of logical components in the process of discovery, which are of interest for philosophers of science. Thus, the context of discovery is an interdisciplinary topic being a subject of reflection whose conclusions may have (and actually have) significant impact on technoscientific research. Although creative mind is the most important "tool" for generation of scientific hypothesis, results of measurements may be the most important among the sources of its inspiration (cf. Chapter 8 of [13] for more details).
The transformation of hypothesis into scientific knowledge in the context of justification requires extensive use of measurement methods and tools. Since the times of Plato, knowledge is understood as "justified true belief". So, its practical definition depends on what is considered to be true, and what is considered to be justified. On the one hand, we refer to at least five co-existing definitions of truth (the correspondence, coherence, consensus, evidence and pragmatic definitions of truth), on the other – we use various patterns of justification, such as: verification, validation, falsification, substantiation, corroboration and proof. Each of them refers to the results of measurement and basic methods of logical reasoning: deduction, induction and abduction (cf. Chapter 9 of [13] for more details).

Regardless of the applied pattern of justification, any piece of information included in the body of scientific knowledge remains uncertain. Unlike scholars of the Ancient Greece, Middle Ages and early modern era, we do not expect certainty of scientific knowledge but rather that it is accompanied by some indicators of its uncertainty. Such indicators are well known in measurement science, and therefore they are primary tools for evaluation of the quantitative uncertainty of scientific knowledge. By extension they are applicable for characterisation of the quantitative uncertainty of mathematical modelling. Unfortunately, they are of little usefulness if qualitative evaluation of the uncertainty associated with mathematical modelling and logical inference is concerned (cf. Chapter 10 of [13] for more details).

6. Concluding remarks
Measurement is an indispensable tool of any mature branch of technoscience, and the philosophy of measurement is an integral part of the philosophy of science. Those facts are not properly reflected in the courses on philosophy of science and research methodology, addressed to the entrants in the research profession (such as Ph.D. students) and to the research practitioners in technoscientific disciplines. On the one hand, the number of such courses across leading academic institutions of the world is relatively limited, on the other – they are given by philosophers who are inclined to underestimate the importance of measurement for productive implementation of the scientific method. While replacing philosophers with experienced research practitioners would be counterproductive, a hybrid solution consisting in the inclusion of the latter in the teaching process could be a partial remedy for the difficulties of the current situation.

There is also an important ethical motivation behind attempts to reintroduce philosophy of science and research methodology in the graduate curricula: ignorance in this respect may be (and most probably is) a cause of growing incidence of scientific misconduct. The first imperative of any professional ethics is "to honestly do one's job". Unlike in the case of a ditch-digger job, the explanation of what does it mean to honestly do a research job requires a semester-long academic course rather than five-sentence instruction. The young researchers, who have not been exposed to an appropriate methodological training, are at risk to err in real-world research situations whose complexity is growing from day to day. They are also prone to run into scepticism when seeing on the every-day basis how much research practice diverges form the naïve definition of the scientific method – its only definition that they have learned at school.

References and endnotes
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