Physicists’ conceptions about the nature of theoretical physics

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Abstract. Scientists’ conceptions of their discipline give interesting insights in authentic scientific practice. The existing studies about scientists’ view of nature of science are rare. Schwartz & Ledermann (2008) were not able to identify clear differences between the conceptions from scientists from several disciplines. Only the ones from theoretical physicists differ from the ones from other scientists. The aim of the current study is the reconstruction of conceptions from researchers in the field of physics about the nature of physics. Here the comparison between experimentally and theoretically working physicists is particularly interesting.

1. University lecturers’ conceptions about the nature of physics

One goal of physics education at school and university is that students should learn something about the nature of physics. In the National Science Standards, it is written that “Students should develop an understanding of what science is, what science is not, what science can and cannot do, and how science contributes to culture” [1]. To fulfill this objective, it is necessary that teachers at school know something about the nature of science. Therefore, it should be part of the curriculum at university for physics teacher students. Their conceptions about the nature of physics are also influenced by their lecturers comparable with teachers and students at school. As teacher’s conceptions are an important research field, scientists’ conceptions should also be investigated.

1.1. Lack of investigation

In contrast to studies that examine conceptions about the nature of science (NOS) of students or teachers at school there is a lack of investigation that focuses on conceptions of scientists and university lecturers. Their beliefs are important as well, because also within the courses at university the lecturer can influence his or her students’ conceptions.

There is another lack of investigation that belongs to the instruments that are used for collecting data. Questionnaires like VNOS or VASS have items that belong to science in general and are based on the consensus view [2]. But „the consensus view […] is blind to the differences among scientific disciplines“ [3]. Several authors claim to consider the differences among the scientific disciplines more and explore views about nature of physics/biology/chemistry [3,4]. Especially for domain specific topics (e.g. theories, law, role of models, role of mathematics) it seems to be useful.

This present study has the goal to bridge this gap and investigate physicists’ conceptions about the nature of theoretical physics.

1.2. Scientists’ conceptions

Often scientists have only a naïve or informed but rarely a sophisticated understanding about the NOS [5]. Most of the scientists emphasize the empirical base of scientific knowledge and ignore the possibility to gain findings just with theoretical-mathematical methods. It is nearly impossible to see any clear differences between the disciplines (e.g. biology, chemistry, physics) and corresponding
research approach (e.g. experimental, theoretical). Only the theoretical physicists differ from the other scientists [6].

In the context of teacher education at university it seemed to be fruitful to analyse the views of involved lecturers and to look for differences between the scientists in detail and focus more on domain specific characteristics – in this case the distinction between experimental and theoretical work in physics.

2. What is theoretical physics

The question what theoretical physics actually is, isn’t very easy to answer and it is not possible to sum up in some sentences, because different aspects should be considered.

Based on literature (e.g. [7], [8], [9]) and discussions with physicists (as a part of the preliminary studies) I finally found five important aspects (Figure 1) that should be discussed while thinking about the nature of theoretical physics.

In this paper I will focus on just two aspects: the interplay between experimental and theoretical physics and the mode of working and thinking in theoretical physics.

2.1. Interplay between experimental and theoretical physics

The relation between experimental physics and theoretical physics is characterized by the interplay between experiment and theory. At this point I will give just a short insight in the discussion about the interplay between experiment and theory. I refer to a description of the interplay given by David Hilbert [10]. He distinguishes four different cases how the interplay could be shaped (Figure 2). For example, he describes the case, when there is an experiment, this is not understood and there upon a theory is developed (Case A).

In the second case there is at first a theory and afterwards an experiment is conducted that will verify or disprove the theory (Case B). In the third case (C), that is described by Hilbert, the experiment has a leading function. Through the experiment a completely new field is discovered, like it was when Röntgen discovered the X-Ray, another example would be the experiment of Oersted. Hilbert also sees the possibility that experiment and theory develop on their own and independent from each other (case D). But later it can be seen that there were done experiments that support the theory.
Probably these four cases are too simple to describe the relation between experiment and theory adequate. Maybe it suggests a linear way of gaining new findings, but Hilbert emphasizes the complex character of the interplay and the strong connection and the interdependence of experiment and theory. It is important to realize that there is not only “case A” but also a huge range of possibilities to gain findings in physics. For this study these four cases are helpful and important for the analysis of the empirical data. The developed system of categories consists of deductive categories based on these four cases of the interplay.

2.2. Mode of working and thinking
To characterize and describe the nature of theoretical physics another important aspect besides the interplay is the question “How theoretical physicists work and think?”. At first mathematical methods would come to somebody’s mind. Because of the huge importance of mathematical methods, the role of mathematics was analysed separately and is not part of this article [11]. Therefore, in this section the question is, what methods apart from “pure” mathematics does theoretical physicists deal with.

In philosophical and historical texts from physicists and philosophers you can find indications for other important modes of working and thinking. One interesting source are letters and talks from Albert Einstein (e.g. [12], [13]). For him science and philosophy of science are closely linked. Einstein explains in one letter to his friend Maurice Solovine his so called EJASE-process – a model of theory building [14]. It is not possible to explain this process in detail in this article. In this place it is just important to highlight two elements of the EJASE-process: the J and A. A stands for the system of Axioms and J for the Jump from the real world to the axioms. For doing this jump Einstein explains that creativity and intuition plays an important role. So axiomatization and creativity/intuition are two aspects we have to think about in detail while speaking about working and thinking in theoretical physics. All important aspects that should be discusses are represented in the following figure.

![Figure 3. Aspects of the methods and mode of working and thinking of theoretical physics.](image)

For the other three aspects, I want to give exemplary quotes, that shows the meaning of these aspects. According to Yves Gingras, a Professor for history and philosophy of science, analogies are an important tool for the daily work of a theoretical physicist: „They [formal analogies] are part and parcel of the theoretical physicist tool-kit.” [15]. Formal analogies are characterized by the same mathematical structure/syntax for two different physical systems (e.g. sound waves and light waves). „The modeling method is one of the most important research methods in theoretical physics.” [16]. All in all models play a significant role in physics at all and were often seen as a link between experiment and theory (Figure 4).

![Figure 4. Models as mediators between experiment and theory (1 Development models, 2 Interpretation models).](image)

Models are a bridge between experiment and theory as a kind. Greca and Moreira for example say „the relationship between theory and reality is always mediated by some physical model“ [17]. Already the
title of the book from Morrison and Morgan „Models as Mediators“ communicate the same perception [18]. The call models mediating instrument. The double arrow not only illustrates the complex character of the interplay and the strong connection and the interdependence between experiment and theory, it is also possible to distinguish between two different kind of models [19]. Development models are very useful and necessary to come up with a theory based on experiments (arrow number 1 in figure 4). The way back means developing experiments for verifying an existing theory. For this step Interpretation models are important because of the high complexity and high level of abstractness of the theories (arrow number 2 in figure 4).

While speaking about models it is also necessary to think about simplification, idealization and approximation. Doing physics without simplification is not possible: „Although QFT is one of the most fundamental theories we have, idealizations are used extensively in the context of working with this theory and constructing models of it.” [20].

In this short section about the mode of working and thinking it was just possible to name the important aspects and not to justify and explain them in detail.

3. Research questions

The research aim is the reconstruction of conceptions of researchers in the field of physics about the nature of theoretical physics. In the end these conceptions are compared with the ones from students at university and will be evaluated. The main research questions are:

- What conceptions do university lecturer in physics and physics education have about theoretical physics?
- Which differences between experimental physicists, theoretical physicists and physics education researchers can be identified?

In this article I want to focus on two aspects: the methods of theoretical physicists (e.g. role of models and simplification) and views on the interplay between experiment and theory.

4. Method

For answering these research questions, an explorative-qualitative study was conducted. In the main study an open questionnaire was used.

4.1. Preliminary study

For developing this questionnaire, there was done a preliminary study – discussions with physicists (N=6) about the question what aspects should be considered for describing the nature of physics and especially theoretical physics. With the help of these discussions it was possible to clarify what aspects should be considered in the questionnaire for the main study. In the end it can be seen that the theoretically found aspects (presented in section 2) were adequate and enough. Indeed, the experts pointed out two aspects (the role of mathematics and the contribution to culture) whose meaning in literature were not that big.

4.2. Main study

The central element of the questionnaire for the main study is the task for the respondents to write a text – comparable to an essay. This text is structured by open questions, that pick up the aspects that were mentioned in section 2 and confirmed in the preliminary study. According to that the respondents had to write a guided essay about the question: “What is theoretical physics?” and they should, for example, consider aspects like the interplay between theory and experiment, the mode of working and thinking in theoretical physics or the role of mathematics.

4.3. Sample

The questionnaire was presented to three different groups of university lecturers: experimental physicists, theoretical physicists and physics education experts (N=17). All these persons are involved in teacher education at university and give lectures in theoretical or experimental physics for those who become a teacher. The group of physics education experts has either his or her research field in
the nature of physics or role of mathematics in physics education or the expert has done his or her Ph.D. in theoretical physics and switched after that to physics education research.

4.4. Data analysis
For analyzing the texts, the qualitative content analysis was used [21]. Developing categories in a deductive and inductive way was one main part while doing content analysis. In the end there was a whole system of categories, several times revised and optimised. With the help of this system of categories it was possible to look for any pattern or regularities. For doing this it was helpful to look for rules for an empirically grounded type construction. Kelle und Kluge describe a step-by-step way for type construction, which I adopted to some extent [22]. At first I developed relevant analysing dimensions with attributes. This dimensions and possible combination of attributes could be seen in figure 5 and 6 – represented as a diagram with two axes. This is the so called “attribute space”. After constructing this attribute space, the cases can be grouped and it is possible to describe empirical regularities, presented in the next section.

5. Results
In this article only two selected examples of the different aspects addressed in the essay will be presented. I will focus on the interplay between experimental and theoretical physics and on the way how theoretical physicists work and think.

5.1. Interplay between experimental and theoretical physics
With the help of the system of categories (attributes at the axis) and case descriptions for every respondent it was possible to locate the physicists and physics education experts in the attribute space you could see in figure 5.

For example, one experimental physicist wrote in his essay the following sentences about the interplay between experimental and theoretical physics. On the one hand he mentioned barriers to collaboration: „Unfortunately the strategies from theorists and experimenters to solve problems are very different, to some extent this complicates collective work […]“ and on the other hand it was also possible to identify a personal opinion with a low appreciation for theoretical physics: „They [theorists] are happiest, if it is possible to pack the event in a formula. With the help of this formula they can calculate the world without depending on experimental physicists.“ There were some quotes like this in his essay, therefore this experimental physicist is located at the intersection of barriers of teamwork/description with a personal valuation in the attribute space.

After locating every respondent in the attribute space, next step was looking for homogeneous groups (highlighted with the gray background in figure 5). The upper group of respondents in the attribute space is for example mainly characterized by focusing on problems and barriers while speaking about the interplay. For them the interplay between experimental and theoretical physics is rather an ideal case than actually realized.

[Figure 5. Attribute space for the interplay between experimental and theoretical physics.]

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**Figure 5.** Attribute space for the interplay between experimental and theoretical physics.
It is also interesting to look for differences between the three disciplines, because the conceptions differ also a lot between the three different groups.

- Theoretical physicists don’t see any problems and describe the interplay very balanced (nearly textbook-like).
- Experimental physicists describe the interplay different (wide range of conceptions): some focus on problems, some give a balanced description or a description with a personal valuation.
- Physics education researcher have a very sophisticated view of the interplay. They either highlight problems that occur or the complexity of the interplay.

5.2. Mode of working and thinking

For searching for response pattern all physicists were located again in an attribute space (Figure 6). The first analysing dimension (x-axis) correlates with conceptions about the role of simplification and contains information if models and simplification were mentioned, just models or both very rarely. The y-axis represents different modes of thinking and working. There is a trend from “soft” thinking and working skills (like creativity or intuition) to “hard” thinking and working skills (like mathematical methods). In between this scale you can find for example axiomatization – the use of first principles for constructing theories. If only mathematical methods were mentioned the respondent was located in the upper level of the y-axis. If also other aspects played an important role for describing the working and thinking of theoretical physicists, the respondent was located in a lower level. An example for that is the following quote from a theoretical physicist: „The construction of new theories results from „looking sharp” and needs new ideas for the understanding of the phenomena. Therefore, intuition for physics […] and creativity are necessary.“ According to these rules all respondents were located in the following attribute space.

Figure 6. Attribute space for the mode of thinking and working and the role of simplification.

In figure 6 it can be seen, that experimental physicists and physics education experts emphasize mainly the work with mathematical methods. Theoretical physicists underline also aspects like elegance and beauty of theories or the role of creativity and intuition.

The experimental physicists attract attention because when they are speaking about simplification they do it in a negative way. For example, when they say: “experimental physics: experiments in the foreground, theoretical physics: just model conceptions” (just was highlighted from the respondent). Another experimental physicist said: “Idealized model assumptions doesn’t fit very well with real processes. These processes are usually much more difficult and more complex than theorist would like.” In contrast to that other experimental physicists also mention the advantage, benefit and need for models and simplification.

5.3. Summary
One important result is the fact, that the conceptions differ between the three different groups (theoretical physicist, experimental physicist and physics education researcher). Table 1 gives an overview for the conceptions about the interplay and the mode of working and thinking.

Table 1. Physicists’ conceptions about the interplay between experimental and theoretical physics and the mode of working and thinking

| Interplay                        | Mode of Working/Thinking                                  |
|----------------------------------|-----------------------------------------------------------|
| **Experimental Physicist**       | describe it very different: focus on problems, balanced description, with personal assessment emphasize mainly the work with mathematical methods |
| **Theoretical Physicist**        | do not see any problems, describe it very balanced (textbook-like) underline also aspects like elegance and beauty of theories or the role of creativity and intuition |
| **Physics Education Researcher**| have a very sophisticated view of the interplay and highlight the complexity or problems that occur emphasize mainly the work with mathematical methods and the role of models and modelling |

6. Discussion and implications

From the essay it can be inferred that scientists’ conceptions about the nature of theoretical physics are shaped by their daily work, main research fields and differentiate between experimental physicists, theoretical physicists and physics education experts. This study could confirm existing results [4,5] and also complement them. Schwartz & Ledermann couldn’t see any clear pattern behind the data. But there was one exception: the group of theoretical physicists differ from the other scientists like biologist or chemist [7]. This present study was a fruitful following investigation, because now it is not just possible to see the differences in comparison to other scientists in general. With the help of this study we know that there is also a range between physicists’ conceptions about the nature of physics and how these differences look like.

For students at university it could be very interesting to read the essays and get an insight in the conceptions of physicists about their own work. This authentic insight into physics research would be very important because many students whose conceptions were also investigated criticize that they do not know a lot about the theoretical–mathematical work in physics although it plays a central role in physics teacher education in Germany.

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