Student's representations about the role of experiment, law, model and theory in physics

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Abstract

In physics, knowledge is acquired, structured, and verified through many tools: experiments, laws, models and theories. The relationships between these tools are very close and very subtle. They are seen differently by the diverse epistemological currents. What are the meanings of these concepts according to students' representations and what links them? This is the critical question which was submitted to third-year graduate physics students at the Ecole Normale Supérieure-Kouba (Algiers). The results, after being sorted out statistically, are analyzed and commented. These results reveal a representation of students based on empiricism and on inductive reasoning.

Keywords: Physics education, physics tools, student's conceptions

Resumen

En física, el conocimiento es adquirido, estructurado, y verificado a través de muchas herramientas: experimentos, leyes, modelos y teorías. Las relaciones entre estas herramientas son muy cercanas y muy sutiles. Ellas son vistas diferentemente por las diversas corrientes epistemológicas. ¿Cuáles son los significados de estos conceptos de acuerdo a las representaciones de los estudiantes y qué los liga? Esta es la pregunta crítica la cual ha sido enviada los estudiantes graduados del tercer año en la Ecole Normale Supérieure-Kouba (Argel). Los resultados, después de haber sido sorteados estadísticamente, son analizados y comentados. Estos resultados revelan una representación de los estudiantes basados en el empiricismo y el razonamiento inductivo.

Palabras clave: Educación en Física, Herramientas de la física, concepciones de los alumnos.

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I. INTRODUCTION

Several studies in science education have shown that difficulties in learning are due in part to the performances of learners, particularly those relating to concepts (Tiberghien [1], Berthou-Gueydan [2] and Kapucu § Yildirim [3]). The misconceptions of learners are sometimes conveyed by teachers themselves (Orlandi [4] and Roletto [5]). It is well known that these misrepresentations are a source of difficulties in the didactic transposition (see for example Halloun [6], Heywood [7] and Métioui [8]). This paper analyzes the performances of undergraduates in physics related concepts: experience, law, model and theory. In paragraph 1, we try to identify the main ideas brought by these concepts and that, based on the work of epistemologists and educationalists. The questionnaire that has raised the representations of students involved is described in paragraph 2. The answers, displayed graphically, are analyzed and commented in the same paragraph. Finally, the conclusion summarizes the responses of students and gives the final results of this work.

II. EXPERIMENT, LAW, MODEL AND THEORY IN PHYSICS

A. What is Experiment?

Experimentation in physics consists in setting experiments in order to, either study a phenomenon, test a theory (or a law) or increase the precision of a physical quantity. The proposed definition for this concept by Develay [9] is*: "experimentation is a synthetic examination of one or several phenomena that are meticulously observed in order to obtain a precise result (a hypothesis checking)"*. There are three levels in experimentation:

i) Observation and description
ii) Induction (generalization)
iii) Deduction

Experiment plays evidently a very important role in physics and other experimental sciences, but it is not very clear whether experience comes before theory or after it. One goal of this study is to know the response to this question according to students.

B. The nature of physical law

The laws of physics are, according to Carnap [10], *"statements that express as precisely as possible the patterns observed in nature"*. It is commonly accepted that laws are used to explain facts already known and to provide facts that are not yet known. For example, Titius-Bode's law, formulated in 1772, allowed the expressing of the distances of the planets (more exactly, the semi-axes of their orbits about the Sun expressed in astronomical units) known at that time with an arithmetic series as follows:

$$r = 0.4 + 0.3 \times 2^{n-1}. \qquad (1)$$

However, the value $n = 4$ did not match any planet known at the time. The discovery of the belt of asteroids led to think that it came from an ancient planet which had disintegrated. The largest asteroid in this belt, recently classified as a dwarf planet, revolves around the Sun at a distance that was approximately provided by Titius-Bode law. This law was also used by Leverrier to calculate the distance of Neptune which was a hypothetical planet at that time.

There are several types of physical laws:

-The qualitative laws like the following: *"gold is a yellow metal and a good conductor of electricity"*.

-The numerical laws such as the ideal gas law:

$$PV = Const. \qquad (2)$$

-The quantitative laws, which depend on universal constants as, for example, Planck's law which gives the energy of quanta as a function of radiation frequency:

$$E = h\nu. \qquad (3)$$

-The causal laws like the fundamental relationship of dynamics between force and acceleration through the inertial mass:

$$\vec{F} = m\vec{a}. \qquad (4)$$

-The statistical laws as Boltzmann, Fermi-Dirac or Bose-Einstein distribution.

-The probabilistic laws such as those of quantum physics.

Some authors believe that the notion of "natural law" has replaced the notion of "cause" because the latter has a metaphysical connotation. However, we believe that the notion of cause in physics has not disappeared. It has rather been relegated to the level of general principles, and even to the symmetries attributed to space-time.

C. The relationship between law and experiment in physics

According to empiricists like Bacon, Locke and Berkeley, a law is only a summary of observed facts. Ohm's law, for example, is a summary of all the experiments related to the circulation of a current in a resistance and nothing more. For Duhem [11] and Poincaré [12], the laws of physics are pure conventions, that is, the physicist freely sets them and they do not reflect a *"natural order"*. There are two kinds of experiments:

• The pre-theory experiments, which are used to build the theory.

• The post theory experiments, which are used to verify the theory.

D. The status of physical theory

According to Duhem, a theory is *"a system of mathematical statements, deduced from a few principles that are intended to represent a set of physical laws as simply, as completely and as accurately as possible"*. To this end, a theory uses several ingredients: laws, hypotheses, general principles and generalization. A physical theory is characterized by a symbolization, a mathematization, an abstraction and a consistency. It is also characterized by a choice of the experimental facts, an approximation, an explanatory power and a faculty of prediction. The main objective of physical theories is to provide a synthetic and consistent knowledge based on facts and scientific reasoning. For the instrumentalist current of thought, introduced by Duhem, theory is simply a prediction. It does not describe the reality beyond the phenomena. There are several types of theories, the main kinds of them being:

i) The phenomenological theories.
ii) The hypothetic-deductive theories.
iii) The explanatory theories.

However, we can say that a given theory can play these different roles at the same time. Finally, we should stress that theory should not be opposed to experiment, but is this the case for students?

E. What does one mean by the concept of "model"?

The model is a theoretical elaboration which approximates a given set of phenomena. It has been defined by Soler [13] as *"a representative, idealized and open framework that is approximate and schematic, but that is fruitful relative to a given goal"*. The objectives of a model in physics are multiple:

- The description of phenomena
- Their explanation
- The equation layout
- The prediction of new phenomena

The model uses essentially two types of concepts:

- Categorized concepts that allow cutting the real into categories in order to study it. Examples: particles, wave, stars...

- Formal concepts, which are constructed from a reflexive effort, taking into, account the rules for consistency and non-contradiction. Examples: force, power, flow...

There are several types of models and the most common of them are:
-The descriptive model
-The icon model
-The analogical model
-The symbolic model
Obviously, each kind of these models has its own function. Our goal here is to know what students think about models and precisely whether the role of models is to describe phenomena or to explain them.

III. REPRESENTATIONS OF THIRD-YEAR GRADUATE STUDENTS

It is well known that epistemological obstacles play a very important role in cognitive processes (Brousseau [14]). The obstacles studied here are those related to cognitive construction tools in physics. The concepts of experiment, law, model and theory are studied of course in college scientific curricula. However, even though students have the opportunity to study several examples about these concepts, rare are the teachers, to our knowledge, who make a real effort to define them. That is why a questionnaire was made up in order to study students' representations related to the links between the experiment, the law, the model and the theory. We start from the assumption that students' representations rely on an approach similar to empiricism and inductive reasoning.

A. Description of the questionnaire

The questionnaire contains four items consisting each of two questions (see appendix). After submitting the questionnaire to a group of 8 teachers, then to a group of 15 students among the target population, we submitted it to a sample of 97 students in their third year of graduation in physics at the Ecole Normale Supérieure/Kouba in Algiers.

B. Results and discussion

One shows and comments the main results obtained by means of the questionnaire described above and by means of interviews with a number of students concerned by the study. These results and comments are given by items.

-Item 1: Physical laws

Physical laws are not built only from observations and experimental facts but they are also based on assumptions, principles and preliminary paradigms. The question here is to know if physical laws reflect reality (or nature) or no and where they come from. According to the realist school, a physical law describes nature accurately while it is only, according to the conventionalist school, a synthesis of results that would give experiences. The purpose of this question is to know what current of thought akin the surveyed students.

Figure 1 shows the results concerning students' representations regarding physical laws. For item 1.a, and for 74 percent of the students' sample, the laws of physics apply partially to reality (answer B) compared to 17% who gave the answer A (the laws of physics apply perfectly to reality) and 6% gave the answer D (physics laws do not apply to reality!).

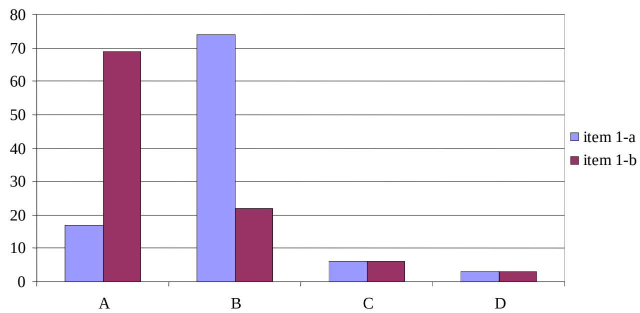

FIGURE 1. Physical laws.

An interview with students who gave the answer C of item 1-a helped refine their answers as follows:
-*"Physical laws are not natural laws and therefore they do not apply to reality"*.
-*"Physical laws are mathematical statements and do not reflect reality."*
-*"Only experiments relate to reality, not physical laws"*.
For item 1-b and for 69 percent of the students' sample, laws of physics are discoveries (answer A) compared to 22% who think that they are mental constructions (answer B) and 6% who gave the answer C (another reply). An interview with students who gave the answer C to item 1.b has raised the following arguments:
-*"Physical laws allow to study and measure phenomena"*.
-*"Physical laws consist in the observation of phenomena, the formulation of hypotheses and on researching links between these phenomena"*.
It comes out from these results that a majority of students take the laws of physics to be discoveries (i.e. they exist in themselves in nature and the physicist simply sheds light on them) and that they fully apply to physical reality. Only 22% of them think that the laws of physics are mental constructions (i.e. the physicist builds them from observations and experimental facts). For 6% of the students, the laws of physics are of an artificial nature and have no direct relationship with reality.

These results show that students' representations are built on a realist epistemology and on the fact that physics is a mainly inductive science.

-Item 2: Models in physics

Figure 2 shows the results concerning students' representations regarding physics models. For item 2-a and for 61% of students, a model applies to some given phenomena (answer B) while 12% of them think that a model applies to all phenomena (answer A) and 21% think that a model does not apply to any phenomenon! These answers demonstrate that the notion of model is understood by the majority of students (61%), but that, however, 21% of them think that a model is unable to describe any phenomenon (this of course raises the question: but what is then the purpose of models in this case?). For Item 2-b and for 67% of students, the role of a model is to explain phenomena (answer A) compared to 21% who think that its role is to describe phenomena (answer B) while 8% gave the answer C (the role of a model is to describe and to explain phenomena). It appears then that the "explanation" function is essential in the eyes of students (88% of them believe that the role of a model is to explain). According to students, the description plays a secondary role. In order to make sure that students understand what a model is, we made an interview with a group consisting of 25 randomly selected students and we asked them to cite models in physics or chemistry.

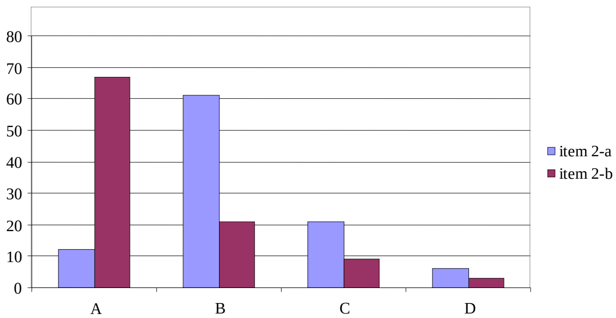

FIGURE 2. Models in physics.

The cited models that were:
- *The "mass-spring" mechanical model (quoted 5 times)*
- *The Bohr model of the hydrogen atom (quoted 11 times)*
- *Lewis chemical bond model (quoted 3 times)*
- *The planetary model of the Rutherford atom (quoted once)*
- *Mendeleyev table (quoted once)*

The fact that the Bohr model is the most cited is due, according to our opinion, to the fact that it is introduced explicitly, both in the course of chemistry and the course of modern physics, as a *"model"*. The *"mass-spring"* model, although more intuitive to explain model vibration phenomena, is quoted only 5 times. This could be due to the fact that the "mass-spring" tandem represents a physical system for most students, and not a model.

-Item 3: Physical theories

Figure 3 shows results concerning students' representations regarding physical theories. For item 3-a, and for 68% of students, physical theory is a set of laws (answer B) against 20% who think that a theory is that which has not yet been confirmed by experiment (answer A). These results show that for most students, the "theory" concept evokes an edifice built from laws and therefore they do not mix between this concept and the "model" concept. However, a non-negligible percentage of students do not trust too much the word "theory" and they tend to equate them with hypothetical statements. This suggests that they attribute to the word "theory" a general meaning related to the adjective "theoretical" and not to the meaning meant by epistemologists. For item 3-b, and for 79% of students, relativity has limited the validity of Newtonian mechanics (answer B) while 6% think that relativity has invalidated Newtonian mechanics (answer A) and 12% chose the answer C.

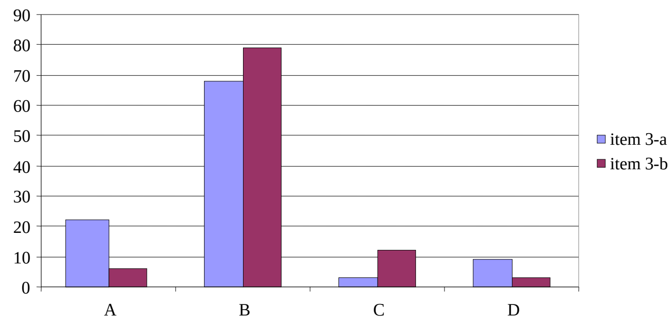

FIGURE 3. Physical theories.

Interviews with students that gave the answer C allowed us to gauge the other alternatives according to them. This gave the following answers:

-Both Newton mechanics and relativity are exact theories.

-Newton mechanics and relativity have no connection with each other.

-Relativity has gone beyond Newtonian mechanics broadening it thus considerably.

Item 2-b results show that most students think that theories evolve, in the sense that a broader theory replaces a theory that is narrow. However, the link between Newtonian mechanics and relativity is not quite clear for 18% of students.

These results reveal a view of students based on a linear evolution of physics. They show also that, according to students, a theory replaces another when it is able to explain more phenomena.

-Item 4: Experiment in physics

Figure 4 shows results concerning students' representations about experiment in physics. For item 4-a and for 55% of students, experiment comes before theory (answer A) against 33% who think that experiment comes after theory (answer B) and 6% who chose the answer C (experiment comes sometimes before theory and sometimes after). These results show that a majority of students believe that experiment comes before theory. This would mean that they see physics as an empirical science. Laws and theories come, according to them, after the experiment. They would therefore be constructed according to an inductive process. A percentage of 33% of students believe however, that experiment comes after the theory. This means that the role of experiment is to verify the theory and, in this case, physics would be a hypothetic-deductive science. For item 4-b, and for 55% of students, the role of experiment is to describe and explain phenomena (answer C) against 25%

who think that its role is to explain phenomena (answer B) and 17% who think that its role is to describe phenomena (answer A).

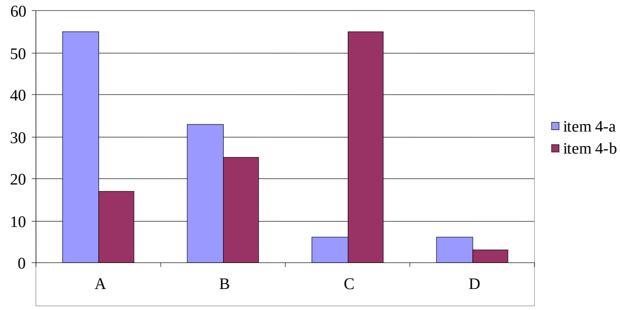

FIGURE 4. Experiment in physics.

An interview with students who gave the answer C of the item 4-a has enabled us to gather the following opinions:

-*Experiment is the surest way to acquire knowledge; it must come before and after the theory.*

-*Experiment provides well-established scientific evidence while a theory is based on speculation.*

-*If theory is not confirmed by experiment, then it is certainly false.*

We see from these answers that, for most students, the role of experiment is to both describe and explain the phenomena. As a result, experiment is, according to them, more important than theory (whose role is only to explain phenomena). Experiment would be a safer way than theory for the acquisition of knowledge. Moreover, theory is valid only if it is corroborated by experiment.

IV. CONCLUSION

We have found that 90% of students who were questioned believe that the laws of physics apply either fully or partially to reality and 70% of them think that the laws of physics are discoveries (in the sense that they preexist until the physicist sheds light on them). Only 20% of them believe that these laws are mental constructions (thus "invented" by the physicist). With regard to the model, approximately 60% of students think that it applies only to some phenomena. From the examples of models that were cited, it appears that this concept is well understood and there is no confusion with the concept "theory". The role of a model is to explain phenomena (about 70% of answers). Physical theory is seen by 70% of students as being a set of laws, but a significant percentage of them (20%) believes that theory is that which has not yet been confirmed by experiment. It seems to us that this answer is due to the confusion between the word "theory" and the adjective "theoretical" (in the ordinary meaning of the term). With regard to the experiment in physics, a majority of students (55%) think it comes before the theory. This emphasizes the fact that the privileged learning method for these students is induction. The answers given in these interviews confirm this conclusion.

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APPENDIX

QUESTIONNAIRE RELATING TO THE ROLE OF EXPERIMENTS, LAWS, MODELS AND THEORIES IN PHYSICS

Note: *this questionnaire is not an exam (do not write your name on the sheet) but a means of evaluation of the teaching of modern physics course (your answers can help improve this teaching). Please answer the questions by putting a cross in front of the chosen answer. If you are not sure, you can choose the answer "I don't know". Thanks for your participation.*

Item 1: Physical laws
Item 1.a: For you, the laws of physics apply to nature:
- ☐ **A-** Perfectly
- ☐ B- Partially
- ☐ C- Do not apply
- ☐ D- I do not know

Item 1.b: Laws of physics are for you:
- ☐ **A-** Discoveries
- ☐ **B-** Mental constructions
- ☐ **C-** Another answer
- ☐ **D-** I do not know

Item 2: Models in physics
Item 2.a: For you, the physics model applies to:
- ☐ **A-** All phenomena
- ☐ **B-** Some phenomena
- ☐ **C-** No phenomenon
- ☐ **C-** I do not know

Item 2.b: The role of a model in physics is to:
- ☐ **A-** Describe phenomena
- ☐ **B-** Explain phenomena
- ☐ **C-** Describe and explain them at the same time
- ☐ **D-** I do not know

Item 3: Physical theories
Item 3.a: For you, a physical theory is:
- ☐ **A-** What has not yet been confirmed by experiment
- ☐ **B-** A set of physical laws
- ☐ **C-** Another answer
- ☐ **D-** I do not know

Item 3.b: The relativity theory has, according to you:
- ☐ **A-** Invalidated the Newtonian mechanics
- ☐ **B-** Limited its validity
- ☐ **A-** Another answer
- ☐ **B-** I do not know

Item 4: Experiment in physics
Item 4.a: According to you, experiment comes:
- ☐ **A-** Before theory
- ☐ **B-** After theory
- ☐ **C-** Sometimes before theory and sometimes after
- ☐ **D-** I do not know

Item 4.b: The role of experiment in physics is, according to you, to:
- ☐ **A-** Describe phenomena
- ☐ **B-** Explain phenomena
- ☐ **C-** Describe and explain them at the same time
- ☐ **D-** I do not know