The role of the paradoxes arising from the limited applicability of the scientific models in Physics Education

EDVCATIO PHYSICORVM
QVO NON ASCENDAM?

ISSN 1870-9095

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(Received 3 August 2021, accepted 18 November 2021)

Abstract
In this article, we consider the role of the scientific paradoxes in physics education connected with basic limit transition models. We present an overview of the most significant paradoxes and aporias in physics. The benefits of using such paradoxes in teaching physics are discussed. A possible algorithm for the implementation of such an active learning method is also described.

Keywords: Physics model, paradox, aporia, active learning.

Resumen
En este artículo, consideramos el papel de las paradojas científicas en la enseñanza de la física en relación con los modelos básicos de transición límite. Presentamos una visión general de las paradojas y aporías más significativas de la física. Se discuten los beneficios de usar tales paradojas en la enseñanza de la física. También se describe un posible algoritmo para la implementación de dicho método de aprendizaje activo.

Palabras clave: Modelo de física, paradoja, aporía, aprendizaje active.

I. INTRODUCTION

The modern paradigm of fundamentalization of physics education requires the creation and use of teaching methods based on a model approach in the study of physical objects, interactions, processes, phenomena, and laws [1]. As a basis of the model approach, the principle of concentration of study material of general and theoretical physics around the most important ideologically and practically meaningful scientific models can be chosen. The means of practical implementation of this principle in teaching physics course is to present the content of each section of the course in a form of a structured system of the basic scientific models.

Therefore, the scientific ideal physics models are one of the most common classes of concepts, which are considered in the high school or university course of physics. Among them there may be cases where [2]:

-we can ignore or neglect some minor variables and their effects;
-we do not describe some variables;
-we image the limiting case for some variables;
-we assume constancy and uniformity of some variables.

The role of models in science and education is discussed in many papers. For example, Etkina *et al*. point to the explanatory and predictive power of idealizations, which have limitations [3]. Due to the not clearly defined limits of applicability, the idealizations refer to a class of fuzzy concepts [4]. This fact causes the necessity of using situated learning, while studying such abstract objects [5]. Wherein, it is preferable to consider as real-life cases, when a particular model correctly describes the phenomenon both quantitatively and qualitatively and when only a qualitative agreement is achieved and even the situations, when a qualitative discrepancy takes place. The extreme degree of this discrepancy is, in fact, a physical paradox.

The paradox is the philosophical concept and is a subject of many books and papers in mathematics, logic, and philosophy. With all the conventionality of the classification of physical paradoxes [6], two polar cases can be distinguished, namely: paradoxes arising from factual, logical, or methodological errors in reasoning or interpretation of the results and paradoxes resulting from moving beyond the framework of applicability of the physical model or its internal contradiction. Paradoxes of the first type are often and readily used in teaching. Paradoxes of the second type rarely appear in physics courses, although they have played an important role at certain stages in the development of science.

At first glance, it seems that a "correct" and consistent theory should be completely devoid of any paradoxes. However, according to the Gödel's incompleteness theorems, the use of any model theory will sooner or later lead to the appearance of a certain paradoxical situation that cannot be resolved within the framework of this model. At the same time, moving beyond the applicability framework of the used model often happens unexpectedly and can not be predicted in advance.

Among the paradoxes, we can distinguish paradoxes as such, aporias and antinomies. A paradox is a situation that can exist in reality, but does not have a strictly logical explanation within the framework of the ideal model used. Aporia is a logical deduction from a certain theory that can not exist in reality. Antinomy is characterized by the presence of two contradicting, equally provable judgments within a single theory. The striking examples of antinomies in physics are wave-particle duality and the antinomy of the continuous and discrete structure of matter.

The paradoxes that influenced the development of science caused by internal contradiction of physical model or going beyond on its limits applicability are called scientific paradoxes. The paradoxes constructed as a kind of partial training model, and often used in learning are called learning paradoxes. In this article, we intend to analyze the role of the scientific paradoxes in physics education connected with basic limit transition models. The next two sections will present an overview of the most significant paradoxes and aporias in physics. In the last section, we discuss the benefits of using such paradoxes in teaching physics and the peculiar properties of their implementation in the learning process.

II. THE PARADOXES

As it is known, the point particle is an idealized zero-dimensional object with only translational degrees of freedom. From this point of view, the Magnus effect, consisting of the deflection of the path of the spinning body of finite dimensions in a resisting medium, is clearly paradoxical. The Magnus effect is the phenomenon important in the study of the physics of many ball sports and can also be found in advanced external ballistics.

The rigid body is a basic mechanical model of a solid body in which deformation is zero or so small it can be neglected. The distance between any two given points on a rigid body remains constant in time regardless of external forces exerted on it. It should be noted that rigid-body dynamics with both contact friction and Coulomb friction is failed when we are trying to explain the so-called Painlevé paradoxes [7] or the cause of rolling friction.

Within the framework of the ideal fluid model, we always assume its density to be constant. This model is not able to explain even qualitatively the hydraulic shock, which is a pressure (density) surge or wave caused when a fluid, usually a liquid but sometimes also a gas, in motion is forced to stop or change direction suddenly. This phenomenon commonly occurs, when a valve closes suddenly at an end of a pipeline system, and a pressure wave propagates in the pipe.

The satellite paradox [8] denotes the experimentally observed fact that a satellite in a nearly circular orbit suffers an increase in velocity, when subject to a dissipative drag force. This paradox arises due to neglect of the Earth's gravitational field as the satellite approaches it.

The well known Galileo's principle of relativity is violated in the Michelson-Morley experiment, according to which the speed of light is the same in all inertial reference frames (that is, a paradoxical result from an ordinary point of view). Moreover, Maxwell's equations turned out to be non-invariant under the classical model of Galilean transformations. The result was the introduction of more general Lorentz transformations and the creation of the special theory of relativity.

As is known, an ideal gas does not perform work when expanding into a vacuum, since there are no interaction forces between its molecules. As a consequence, its temperature should remain constant. In fact, for a real gas there is a "paradoxical" Joule–Thomson effect of the gas cooling or heating, when it is forced through a valve or porous plug while keeping it insulated. The gas-cooling throttling process is commonly exploited in refrigeration processes such as air conditioners, heat pumps, and liquefiers.

The well-known model of a point charge is not able to describe even qualitatively the "paradoxical" effect of attraction of like-charged conducting bodies [9], arising as a result of the phenomenon of electrostatic induction. Within the framework of the model of harmonic oscillator it is impossible to qualitatively explain the aperiodic regime of motion in the presence of dissipative forces and the dependence of the oscillation period on the amplitude in the case of large oscillations.

For the model of a point light source, it is paradoxical that the penumbra is appearing from an obstacle of finite dimension. A thin optical lens model in no way can predict the interesting effect that a biconvex glass lens of sufficiently large thickness becomes a diverging lens in air [10].

The paradox of the quantum tunneling is the statement that the ability of microparticles to pass through a potential barrier with a height greater than their total energy, allegedly contradicts the law of conservation of energy (the classical mechanics model). This paradox is resolved within the framework of quantum mechanics and may be explained in terms of the Heisenberg uncertainty principle (the wave nature of microparticle).

III. THE APORIAS

A common aporia occurs with mathematical idealizations such as point sources, which describe physical phenomena well at distant or global scales, but break down at the point itself (the field strength turns to infinity at this point). Another aporia due to mathematical idealization is D'Alembert's paradox of fluid mechanics. When the forces associated with two-dimensional, incompressible, irrotational, inviscid steady flow across a body are calculated, there is no drag. This is in contradiction with observations of such flows, but as it turns out a fluid that rigorously satisfies all the conditions is a physical impossibility. The mathematical model breaks down at the surface of the body, and new solutions involving boundary layers have to be considered to correctly model the drag effects.

The famous aporia associated with the rigid body model occurs, when we consider the statically indeterminate or hyperstatic structures. In this case, the static equilibrium equations (force and moment equilibrium conditions) are insufficient for determining the internal forces and reactions on that structure. To solve statically indeterminate systems (determine the various moment and force reactions within it), one considers the material properties and compatibility in deformations, that is, turn to the deformable body model.

The kinetic energy paradox is a thought experiment within the framework of classical mechanics, allegedly indicating a violation of Galileo's principle of relativity. When the speed of a body changes, the increment of its kinetic energy in one frame of reference is not equal to the increment in another frame of reference. This supposedly implies the existence of reference frames, where the law of conservation of energy is violated, and, as a result, Galileo's principle of relativity is allegedly violated too. This aporia is resolved by taking into account the change in the kinetic energy of an external object (for example, Earth) interacting with the body. This paradox can be used to assimilate students of such an idealized concept as a closed system (see also the satellite paradox considered above).

The Neumann-Seeliger paradox is a paradox of the classical Newton’s theory. It states that in an infinite Universe with Euclidean geometry and non-zero average density of matter, the gravitational potential everywhere takes an infinite value. This paradox is completely eliminated within the framework of Einstein's general theory of relativity.

The Loschmidt's theoretical paradox is associated with the statement that for any mechanical system, due to the time reversibility of the equations of the model Newtonian dynamics, a sequence of states with decreasing entropy is possible. This paradox is explained by the fact that for mechanical systems with a large number of particles (that is, for statistical systems), spontaneous returns to the already passed sequences of states have extremely low probabilities, their evolution in this sense is irreversible (that is, there is a so-called "arrow of time").

The heat death paradox is the theoretical hypothesis put forward by R. Clausius in 1865 on the basis of extrapolation of the second law of thermodynamics to the entire Universe. According to Clausius, the universe should eventually come to a state of thermodynamic equilibrium, or "heat death" with maximum entropy. One of the arguments against this hypothesis is based on the idea of the infinity of the Universe, so that the laws of thermodynamics, based on the study of objects of finite size, are not applicable to the whole Universe in principle.

A very famous unphysical theoretical prediction is the “ultraviolet catastrophe”, according to which the spectral distribution functions of an ideal black body model at thermal equilibrium turns to infinity as wavelength tends to zero. The ultraviolet catastrophe results from the equipartition theorem of classical statistical mechanics and is eliminated by Planck's assumption about the discrete structure of radiation.

IV. THE ROLE AND IMPLEMENTATION OF THE SCIENTIFIC PARADOXES IN PHYSICS INSTRUCTION

First, we note that the presence of this kind paradoxes leads to the development of science by constructing generalized physical models and theories. For example, the existence of singularities within a certain scientific model suggests the necessity of introducing some "cut-off" or "blurring" factors. In this regard, the resolution of these paradoxes together with students facilitates primarily the development of their physical thinking, to the ability to acquire knowledge by themselves. In this case, the role of using the mathematical tools undoubtedly increases too. The using of physical paradoxical situations implies clear answers to the questions “what? where? How?". When this should be borne in mind that each new knowledge should generate a new degree of development of thinking.

From a psychological and pedagogical point of view, the use of paradoxical situations in teaching is associated with a departure from absolutization of models application, with the ability to use them situationally. Conflict-free teaching always leads to absolutizing concepts and representations, which inevitably entails formalism in knowledge. Moreover, the physical paradoxes can cause certain experiences (emotional, ethical, and aesthetic) in students and thereby "revive" the process of grasping rather abstract concepts. The inclusion of scientific paradoxes into the educational process contributes not only to the acquisition of new knowledge, but also to a deep understanding of the educational material studied. In addition, the amazing facts, as it is known, are imprinted in human memory for a long time or forever. Therefore, we believe that scientific paradoxes can serve as key (memorable) points in the presentation of educational material for a physics course.

Finally, the presence of a paradoxical situation, associated with the existence of internal contradictions describing the behavior of the same object, increases the motivation for learning and gaining new knowledge [11], since it is a kind of challenging problem that enhances students’ beliefs about the importance and value of the task and their critical thinking.

Let us now turn to the issues of the implementation of scientific paradoxes in the educational process. First of all, we note that the method of using paradoxes is, in fact, one of the methods of active learning (the student-centered approach). In this case, however, the following requirements should be imposed on it:

1. The teacher initially formulates a certain problem situation (asks to explain a certain experimental fact or theoretical statement within the framework of some ideal model). If necessary, he asks students to make calculations based on a certain theory and formulate this paradox themselves.
2. At the second stage, a discussion and problem analysis should take place in the class and it is concluded that this paradox is due to the limited use of the chosen model.

3. Next, the teacher puts forward some hypothesis (new model or theory), briefly outlining the history of its appearance.
4. At the last stage, students make attempts to explain or calculate the considered effect within the framework of the extended model and conclude that it is resolved only when the model is used.

We emphasize that at almost all these stages, the students are forced to be active participants in the learning process.

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