Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Quantum Theory Presentation in High School – a Unique Opportunity

Igal Galili

igal.galili@mail.huji.ac.il

Hebrew University of Jerusalem

Avraham Merzel

Hebrew University of Jerusalem

Research Article

Keywords: Quantum theory education, Secondary school physics, Physics curriculum development, Nature of science, Scientific theories, Discipline-Culture paradigm, Theory-framed instruction

Posted Date: November 19th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11628176/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Teaching quantum theory (QT) in secondary school is constrained by two severe limitations: minimal instructional time and a mathematical level far below that required for formal quantum mechanics. Just these constraints create a unique opportunity. Prevented from focusing on mathematical competency, teachers are compelled to deal with the conceptual foundations of QT as a fundamental theory—its structure, core principles, epistemological commitments, and characteristic features of scientific knowledge. Mathematical tools do not disappear but used in a less explicit, more symbolic form. Traditional “Modern Physics” approaches, which present a short historical sequence of quantum discoveries, used to offer a collection of surprising phenomena and fail to convey the image of QT in parity with classical mechanics, electromagnetism, and optics. Building on recent research, this paper proposes a theory-framed, discipline-culture (DC) structure for a 30-hour high-school QT curriculum, organizing knowledge into nucleus, body, and periphery. This structure enables explicit comparison between quantum and classical accounts, naturally integrating the Nature of Science (NOS) and revealing science as a family of fundamental theories possessing ontologically different claims but grounded in a shared method. The approach also highlights the heightened demands on teacher expertise, echoing Poincaré’s view that teachers, unlike other practitioners, must possess “a profound and exact knowledge of first principles.” We argue that QT instruction at school level, precisely because of its constraints, can cultivate conceptual maturity and scientific literacy in ways not possible elsewhere in the physics curriculum.

1. Introduction

The situation in teaching quantum physics in schools is unique. On the one hand, Quantum Theory (QT), being at the foundation of our present understanding of nature, is an obvious necessity alongside other classical fundamental physics theories. On the other hand, the claims of QT stand in striking contradiction to our common experience in manipulating and observing material objects around us, and the formalism of QT relies on mathematical tools that lie *mostly* outside the school mathematics curriculum. This dual complexity raises a central question: How should physics educators deal with this challenge?

The first approach taken by physics educators was to follow the historical development of the new knowledge, offering an introduction to the new knowledge through the early-20th-century discoveries that emerged from classical physics. This approach, commonly referred to as *Modern Physics*, was reflected in college-level textbooks [1, 2] that presented a succession of remarkable phenomena at the atomic scale and the pioneering scientific ideas that shaped the construction of quantum theory [3]. These textbooks typically began with black-body radiation, atomic spectroscopy, the photoelectric effect, the Rutherford–Bohr account of the atom, radioactivity, wave–particle duality, and atomic energy (in a ‘story-like’ manner). They then proceeded to topics found in a standard undergraduate course in *quantum mechanics*—the free-particle, the particle in a potential well, tunneling, the uncertainty principle, spin, the

fermion–boson dichotomy, and so forth—arranged sequentially from simpler to more complex. Along the way, several principles of the new physics were stated.

Trying to follow this trend, teaching the school curricula in *Modern Physics*—much more limited in both time and instructional tools—typically end their presentation after only the first few steps. This produces an eclectic collection of surprising knowledge items that cannot create a holistic or adequate view comparable to the classical theories taught in school (not that the later were provided a clear hierarchical structure [4]). A comparative analysis of secondary-school quantum physics curricula across 15 countries shows that variations of this history-based approach are widely practiced [5]. The impact of such teaching is often the impression that classical theory was simply corrected through scientific progress: that scientific knowledge is always approximate, only tentative, unreliable and subject to change, thus reinforcing the image of science as constructing a single, all-inclusive body of knowledge about the world or, even worth, the “pessimistic” view [6] on human technological progress preventing its clear benefits (e.g. use of atomic energy).

Importantly, one should recognize that school-level teaching is not simply a lower step on a homogeneous ladder of education representing increasing complexity. School education, in its original Enlightenment spirit, is intended for a much broader population—even when offered as an elective course. This aspect is rarely acknowledged in the physics education discourse, where school instruction is often treated merely as a preliminary stage leading to college or university study of QT. The present study focuses specifically on school education and seeks to overcome this presupposition which neglects scientific literacy as the proper goal of public schools for broad population including not necessarily specializing in quantum research and technology, after school graduation.

To prepare for the suggested shift in schools, it is useful to note a development that has already somewhat transformed the college and university *Introductory Quantum Mechanics* course [7]. Its traditional sequential canon has been disrupted by a new approach [8, 9]. Instead of beginning with an observable possessing a continuous spectrum (the free-particle wave function), instruction now often starts with an observable of discrete character in its simplest form—a two-level system, the “spin-first” paradigm. This approach introduces the basic principles and formalism of quantum theory through a discrete variable while employing Dirac notation from the outset. Its stronger appeal, and thus its greater teaching efficacy, has been supported by experimental studies [10].

In the school domain, extensive research has been conducted and comprehensively reviewed on teaching *quantum physics* [11–13]. Several recurring claims have emerged across multiple studies: instruction should begin with concepts and experimentally accessible phenomena, emphasize principles, use minimal mathematics, employ Dirac notation, and rely on appealing illustrative experiments and simulations, appealing illustrative experimental settings and simulations [14–18]. However, although quantum mechanics was nominally addressed as a theory, the concept of *theory itself*—its characteristics, structure, and central role—was treated as obvious and required no elaboration. Thus, the study by Merzel and twenty colleagues [19] from seventeen universities in nine countries (eight

European), which identified thirty-six concepts relevant for teaching quantum mechanics, did not include *theory*, the most fundamental concept that relates all others. Against this background, the study by Weissman and colleagues [20, 21] which places *theory* at the center of instruction and explores its structure within the Discipline-Culture paradigm [22], stands out as exceptional.

Furthermore, researchers repeatedly noted that, given the insufficient toolkit available for treating QT and the fact that school education must address a broad population, the curriculum should explicitly engage with the features that characterize science— Nature of Science (NOS). School education is meant to convey enlightenment and scientific literacy, and under these conditions, QT instruction must incorporate NOS rather than rely solely on formalism [5]. To further justify this argument, we may point to its direct relationship with the concept of *theory* in the context of teaching *quantum physics*. Although "quantum physics" and "quantum theory" are often used interchangeably, a distinction of emphasis is useful for the present discussion. While Quantum physics (QP) is a general term denoting the broad field of physics encompassing quantum phenomena, experiments, theoretical accounts, and applications, by Quantum Theory (QT) we mean an inclusive cluster of the same coherent knowledge items, conceptual and mathematical but organized in certain hierarchical structure, identified as a fundamental theory of certain type. It presents a coherent system of principles, concepts, mathematical relations, and empirically supported accounts through which quantum phenomena are explained and predicted [22]. The educational claim of this work is that students should appreciate what makes quantum knowledge such *a theory*. The relationship between the two perspectives manifests itself explicitly in three aspects.

First, teaching QT, with its highly anti-intuitive account of reality, transforms the traditional metaphor of science as a *reflection* of nature. *Reflection*—usually associated with a *mirror* image—is replaced by *modeling*, which is not obliged to exhibit obvious similarity to naïve observation. This maturates students' understanding of physics [23, 24].

Second, the introduction of QT raises the question of the status of *correct* and *incorrect* theories in science. The popular view of science as merely tentative easily leads to the impression that quantum mechanics simply replaced classical mechanics, just as classical mechanics replaced Aristotelian or medieval theories during earlier scientific revolutions. By the same logic, one might assume that quantum mechanics will eventually be declared "incorrect" when superseded by a more advanced theory such as quantum electrodynamics, all within a single, all-inclusive theoretical framework. This image is replaced by the understanding that contemporary science consists of a *family of fundamental theories*, each valid within its own domain of parameter magnitudes. These theories share a common *scientific method*—their epistemology—even though their ontological claims differ [25, 26].

Third, drawing on "common sense" and referring to everyday experience is taken for granted when teaching classical theories such as mechanics, electromagnetism, and classical optics. Teaching QT, however, requires replacing this intuitive plausibility with a system of rules for knowledge production and hierarchical organization. QT demands that students abandon their naïve, uninformed, naturally developed personal sense in some aspects of how the world behaves. Schrödinger's cat thought

experiment can serve precisely this purpose — to illustrate the need of such replacement in the most succinct and striking way [27].

In this essay, we strengthen the claim for the theory-framed approach [21] to teaching QP at the high-school level and show how this approach addresses aspects of physics knowledge that we consider essential—particularly for prospective physics teachers. Our study aligns with the broader framework of science-education activities articulated by Michelini and colleagues, emphasizing the importance of conceptual understanding, epistemological awareness, and the structured organization of scientific knowledge [28].

2. Theory-framed approach

Quantum mechanics — here referred to as quantum theory (QT) to emphasize its organization as a coherent, hierarchically structured system of physical knowledge— is a fundamental theory of the real which *defines* this knowledge domain as scientific. It does not replace or refine classical physics; rather it coexists with it, joining the small group of other fundamental theories. As such, it should appear in physics curriculum [22]. The curriculum then faces a choice: to adopt a disciplinary approach—teaching the theory is presented independently of any other or a cultural-disciplinary, in which the theory is presented while explicitly comparing its basic claims and core principles with their parallels in other fundamental theories, such as classical mechanics. In the disciplinary representation, a theory is structured in terms of a *nucleus* (core principles) and a *body* (derived implications, experiments, explained phenomena). In contrast, the Discipline-Culture (DC) representation structures the theory in terms of *nucleus–body–periphery*, where the periphery consists of alternatives to the nucleus, including classical counterparts or competitive conceptions.

Adopting either the disciplinary or the DC approach already marks a departure from the sequential, historically arranged construction of QT that was common in college-level Modern Physics courses.[1] Principles emerge not necessarily in their chronological appearance (for example, in the past, the principle of non-locality, if appeared, was often reserved for advanced instruction). Arguing for an emphasis on the principles of QT in teaching is not new, nor is the comparison with classical physics [13, 14, 29]. It is common in textbooks, and the claims of quantum mechanics are considered paradoxical precisely because they stand in blunt contradiction to classical account, a context deliberately highlighted in countless examples. If so, what is new?

The main aspect of DC is the explicit articulation of this vision as a framework — a *paradigm* of the curriculum. Once developed, the core structure of such a curriculum could even be displayed on the wall of a physics classroom, much like the periodic table of elements in a chemistry classroom. In both cases, these are the ontological claims about the fundamentals. DC represents cultural knowledge: the polyphony of possible pictures of the world. Although presenting the subject in multiple variations might appear confusing, it is in fact more accessible to human understanding, which naturally relies on comparison and contrast.

Weissman and colleagues reported on an attempt to construct a QT curriculum for 12th-grade physics, planned for 30 hours of classroom instruction. The resulting structure is presented in Table 1. Let us identify the key features of this curriculum framework.

Table 1
The structure and components of the developed curriculum of Quantum Theory at high-school level [21] (*)

Nucleus	**Body**	**Periphery**
Particle-wave duality Light duality Matter duality (de Broglie) Quantum particle (Quanton)	Einstein account of photoelectric phenomenon Thomson Jr. Electron diffraction Double slit experiment with light Double slit experiment with electrons Compton scattering	Classical waves of light and matter Classical light interference in double slit experiment (Young) Small marble balls passing through double-slit screen
Physical state – basis states and compound states Principle of superposition of states Wave function, probability and measurement Uncertainty (indeterminacy) principle (Heisenberg) Momentum and energy conservation	Schrödinger's cat thought experiment 'No trajectory' of electron path in the double-slit experiment Dirac symbolic notation of states Stern-Gerlach two-state system account Wave function in Dirac notations Measurement in Dirac notations Mach-Zehnder interferometer Heisenberg position-momentum indeterminacy (Δx&Δp)	Classical state (x, p), motion, trajectory Classical determinism and uncertainty (Heisenberg's initial interpretation of uncertainty, "microscope") Superposition in classical theory Δx&Δk uncertainty in waves Schrodinger matter waves Electron clouds in atom Bohr model
Operators of physical observables and equation of state Transition between states	Schrödinger equation (in Dirac notations) Discrete and continuous spectrum of observables Potential well and barrier in quantum mechanics Tunneling (Radioactivity, spontaneous transition)	Physical quantities and the equation of motion Potential well and barrier in classical mechanics State stability Discrete and continuous spectrum in classical mechanics

Nucleus	Body	Periphery
Fermions and bosons Pauli principle Bose principle	Atomic structure and spectrum the Periodic Table of elements Photons and Laser	Matter particles, Classical light Single type of mass
Nonlocality Causality Quantum entanglement	EPR thought experiment and Bohm modification for photons Bell inequality and Aspect experiment	Locality-Causality principle Hidden variables interpretation Many-Worlds interpretation

(*) Here, we added several items not used so far in the experimental teaching in order to strengthen the illustration of the curricula approach we advocate.

The knowledge items are grouped in related triads combining elements of the nucleus-body-periphery. The items are not arranged historically. The principles and fundamental concepts are emphasized by placing them in the nucleus, where they are clearly distinguished from the corresponding phenomena and applications in the body, as recommended by numerous educators [29]. The nucleus items were elicited from standard quantum-mechanics textbooks [13, 14, 17, 29], whereas their counterparts in the periphery were deliberately identified and selected. The elements of the *body* were selected to illustrate the principles—for example, the periodic table of elements illustrates Pauli principle for fermions, laser — features of bosons, and tunneling—transitions between states.

The elements of the periphery make explicit conceptual comparison between the principles and concepts in the nucleus and their alternatives, counterparts — whether erroneous or belonging to other theories. Thus, the two kinds of predictive power were contrasted: the *quantum probabilistic* and *classical deterministic*. Similarly, quantum uncertainty in the probability distribution (nucleus) is contrasted with *the statistical uncertainty* of classical mechanics (periphery). Importantly, the principles of *locality* and *causality* which are separated in quantum theory (nucleus) and united in classical (periphery).

Alternative interpretations of quantum theory were addressed selectively [30, 31]. The table includes three interpretations placed in the periphery:

(1) Heisenberg's early interpretation of the uncertainty principle, which attributed uncertainty to the comparable mass–energy of the measuring device and the measured object—*measurement disturbance* ("Heisenberg's microscope");

(2) the *electron cloud* in atom as a material object; and

(3) *local hidden variables* which would presume classical deterministic account for entangled particles.

All three have corresponding nucleus–body contexts that provide their refutation. In contrast, two other famous interpretations—*Bohmian mechanics (BM)* with its nonlocal quantum potential, and *Everett's Many-Worlds interpretation (MWI)*—were mentioned in a different way for their specific characteristics [31–33]. First, they could not be adequately presented within the constraints of the school curriculum. Second, they do not provide unique predictions that differ from the standard Copenhagen interpretation (CI) and therefore cannot be refuted through the scientific method. Yet, because of their intellectually challenging content, they continuously attract students' curiosity by offering alternative ways of understanding formal QT and in a way reconciling its counterintuitive claims with everyday intuition.

Moreover, BM and MWI illustrate the intimate and often mysterious stage of knowledge construction, particularly its subjective *stage of discovery*, which precedes the objective stage *stage of demonstration* or proof [34–36]. Indeed, the alternative interpretations of QT provide a natural opportunity to appreciate this important feature of NOS. They may also increase students' motivation to participate in the construction of scientific knowledge through observing how great thinkers have attempted to comprehend complex reality and by encouraging them to propose their own perspectives, adding another voice to the ongoing discussion, to join the club.

Furthermore, by introducing BM and MWI as alternative interpretations, we introduce a refinement of the DC periphery content organization. One can now distinguish between alternatives to the nucleus that can be refuted (the three mentioned above) and those that cannot (BM and MWI). The existence of such open questions keeps the presented theory alive, stimulates students' imagination, invites their own opinion, and highlights the principle of parsimony, namely the preference of the simplest explanation in scientific practice, while acknowledging the possibility of future clarification or revision.

3. Addressing NOS

Table 1 explicitly represents the ontological content of school teaching QT. In practice, the epistemological aspect of QT —NOS—inevitably emerges in any question raised in relation to this content (How do you know about that? What is reliable in physics? What does it mean correct? Why theories change?). These questions reveal the scientific method that underlies ontological claims, endowing the emerging theory of reality with features such as objectivity, certainty, accuracy, mathematical form, modeling, and experimental grounding within a specific domain of reality [22, 37–39].[2]

At the same time, the explicit correspondence between quantum principles and their classical counterparts—each verified through the same method but in different domains of reality—introduces a new perspective on what *reality* means. Science is revealed in its *polyphonic* nature, captured by humans through different theories, forming a kind of *theatre of theories* in which multiple, valid representations coexist.

In fact, this approach to teaching QT not only illuminates the unique scientific method but also unifies QT with the classical theories, students have previously learned. In doing so, it creates a holistic perception

of physics as a single discipline rather than a mosaic or patchwork of independent accounts. Because QT appears as the final component of school physics —after classical mechanics, electrodynamics and optics — and because severe limitations on mathematical formalism employed during greatly restricted teaching time, teachers gain a unique opportunity to engage students with the conceptual meaning and nature of scientific knowledge. This presents a genuine challenge and requires a high level of maturity of content and pedagogical content knowledge.[3]

Prevented from focusing on an extensive mathematical formalism, teachers are more available to deal with theory as especially arranged cluster of coherent elements. The teacher's narrative expands the conceptual content, the aspects otherwise seldom raised in pragmatic instruction and illuminate on essential features of physics knowledge—not declaratively, but through refinement within the quantum context with minimalistic mathematical support. The new knowledge emerges as possessing features that vary across a range: from objectivity in empirical justification to subjectivity in knowledge creation and interpretation; from high accuracy within defined domains of validity and strong predictive power to the limits of what can be predicted or even considered in QT; from absolute, restrictive principles to tentative interpretations and accounts of phenomena. All these features appear in QT as part of a physics theory—a picture of the world. Under this approach, the *Nature of Science* becomes the subject of a mature narrative that reveals the variation in features, claims, and meanings of concepts.

For instance, the teacher reveals the ways in which QT remains causal, essential in physics since Aristotle. QT extends the meaning of causality to the prediction of probability distributions for variables magnitudes in some settings, while yielding exact values in others. It also shows that QT possesses absolute, non-probabilistic laws and principles—such as conservation laws, the selection rules governing atomic spectra, the fermion–boson dichotomy, and the exclusion principle.

In teaching QT, teachers—perhaps for the first time—can explicitly unify various principles, laws, and rules into a coherent system of knowledge items that together depict a specific domain of reality, create a physical theory. Looking backward, they can point out that students have already encountered several large but distinct clusters of knowledge of this kind in earlier physics instruction: Newtonian mechanics, electromagnetism, and optics—all organized as fundamental theories [22]. QT thus becomes not a mere final topic in learning physics but the culminating example that reveals how physics is structured: as a set of fundamental, domain-specific theories, each internally coherent and epistemologically unified, framed in a disciplinary-cultural structure.

The image of science as a family of fundamental theories standing in parity is reinforced through the systematic comparison between quantum mechanics and classical mechanics—theories that may contradict each other in many respects yet are grounded in the same scientific method. The resulting insight constitutes a significant educational gain: students come to see science as a set of domain-specific frameworks collectively expand and refine our grasp of reality. Furthermore, physics, as being a quantitative paradigm, fosters the examination of the boundaries between these fundamental theories, and demonstrate Bohr's correspondence principle, in which fundamental theories may have similar

(quantitative) predictions for certain phenomena even basing on contradictive conceptions; in terms of DC: overlapping bodies and different nuclei.

Stating all this immediately underscores the special importance of teachers' expertise and, consequently, the critical need for pertinent teacher training [28, 41]. Researchers in physics education consistently emphasize the need for a substantial shift in teacher preparation—one that includes new conceptual and epistemological perspectives on physics learning, moving beyond the traditional neglect of *epistemology* [30, 37, 42]. Only with such preparation can teachers confidently engage with the conceptual depth of QT, articulate its ontological and epistemological dimensions, and guide students toward the much-desired *understanding* of the quantum world.

Table 1 explicitly represents the ontological content of school teaching QT. In practice, the epistemological aspect of QT —NOS—inevitably emerges in any question raised in relation to this content (How do you know about that? What is reliable in physics? What does it mean correct? Why theories change?). These questions reveal the scientific method that underlies ontological claims, endowing the emerging theory of reality with features such as objectivity, certainty, accuracy, mathematical form, modeling, and experimental grounding within a specific domain of reality [22, 37–39].[2]

At the same time, the explicit correspondence between quantum principles and their classical counterparts—each verified through the same method but in different domains of reality—introduces a new perspective on what *reality* means. Science is revealed in its *polyphonic* nature, captured by humans through different theories, forming a kind of *theatre of theories* in which multiple, valid representations coexist.

In fact, this approach to teaching QT not only illuminates the unique scientific method but also unifies QT with the classical theories, students have previously learned. In doing so, it creates a holistic perception of physics as a single discipline rather than a mosaic or patchwork of independent accounts. Because QT appears as the final component of school physics —after classical mechanics, electrodynamics and optics — and because severe limitations on mathematical formalism employed during greatly restricted teaching time, teachers gain a unique opportunity to engage students with the conceptual meaning and nature of scientific knowledge. This presents a genuine challenge and requires a high level of maturity of content and pedagogical content knowledge.[3]

Prevented from focusing on an extensive mathematical formalism, teachers are more available to deal with theory as especially arranged cluster of coherent elements. The teacher's narrative expands the conceptual content, the aspects otherwise seldom raised in pragmatic instruction and illuminate on essential features of physics knowledge—not declaratively, but through refinement within the quantum context with minimalistic mathematical support. The new knowledge emerges as possessing features that vary across a range: from objectivity in empirical justification to subjectivity in knowledge creation and interpretation; from high accuracy within defined domains of validity and strong predictive power to the limits of what can be predicted or even considered in QT; from absolute, restrictive principles to

tentative interpretations and accounts of phenomena. All these features appear in QT as part of a physics theory—a picture of the world. Under this approach, the *Nature of Science* becomes the subject of a mature narrative that reveals the variation in features, claims, and meanings of concepts.

For instance, the teacher reveals the ways in which QT remains causal, essential in physics since Aristotle. QT extends the meaning of causality to the prediction of probability distributions for variables magnitudes in some settings, while yielding exact values in others. It also shows that QT possesses absolute, non-probabilistic laws and principles—such as conservation laws, the selection rules governing atomic spectra, the fermion–boson dichotomy, and the exclusion principle.

In teaching QT, teachers—perhaps for the first time—can explicitly unify various principles, laws, and rules into a coherent system of knowledge items that together depict a specific domain of reality, create a physical theory. Looking backward, they can point out that students have already encountered several large but distinct clusters of knowledge of this kind in earlier physics instruction: Newtonian mechanics, electromagnetism, and optics—all organized as fundamental theories [22]. QT thus becomes not a mere final topic in learning physics but the culminating example that reveals how physics is structured: as a set of fundamental, domain-specific theories, each internally coherent and epistemologically unified, framed in a disciplinary-cultural structure.

The image of science as a family of fundamental theories standing in parity is reinforced through the systematic comparison between quantum mechanics and classical mechanics—theories that may contradict each other in many respects yet are grounded in the same scientific method. The resulting insight constitutes a significant educational gain: students come to see science as a set of domain-specific frameworks collectively expand and refine our grasp of reality. Furthermore, physics, as being a quantitative paradigm, fosters the examination of the boundaries between these fundamental theories, and demonstrate Bohr's correspondence principle, in which fundamental theories may have similar (quantitative) predictions for certain phenomena even basing on contradictive conceptions; in terms of DC: overlapping bodies and different nuclei.

Stating all this immediately underscores the special importance of teachers' expertise and, consequently, the critical need for pertinent teacher training [28, 41]. Researchers in physics education consistently emphasize the need for a substantial shift in teacher preparation—one that includes new conceptual and epistemological perspectives on physics learning, moving beyond the traditional neglect of *epistemology* [30, 37, 42]. Only with such preparation can teachers confidently engage with the conceptual depth of QT, articulate its ontological and epistemological dimensions, and guide students toward the much-desired *understanding* of the quantum world.

4. Some teaching activities related to the DC based curriculum

As mentioned, comparing and contrasting the nucleus and periphery offers a cognitive pathway for assimilation of the key concepts of QP, understanding them as a coherent QT. In this section, we describe examples of teaching activities developed within the DC-based curriculum. We incorporated

these activities into both teachers training programs [41], in which we adopted the ‘teachers as learners’ approach [43], and courses for 12th grade students. The activities are presented here solely to illustrate the implementation of the DC-based approach; empirical evaluations of these implementations have been reported elsewhere.

4.1. Quantum and Classical Physics in comparison

In this task, learners (the teachers participating in a training workshop or students) were asked to read a two-page, non-mathematical text about Born’s probabilistic interpretation. The text compared water and probability waves, different metaphors of the electron (as a marble-like particle, as a spatially smeared cloud, and in terms of probability distribution), and discussed measurement within the Copenhagen interpretation. The learners were then asked to contrast quantum and classical perspectives through completing two tables: one listed differences between the two perspectives and the other – similarities. The learners were asked to identify criteria for the comparison. The learners received tables containing headings and instructions only. The criteria for comparison between the Sun and the Moon were illustrated by roundedness –for similarity and the distance from the Earth – for the difference. Tables 2a and 2b exemplify the received answers.

Table 2

a Differences between classical and quantum physics (Examples of filling. Square brackets mark the topics of the observed discussions.)[4]

Instructions: Identify criteria of difference between classical and quantum objects. For each criterion, specify the difference..		
Subject for comparison	Classical physics	Quantum physics
Wave and particle	Waves and particles are distinct appearances of physical reality.	Wave-like and particle-like descriptions provide complementary accounts of quantum reality.
The meaning of “wave”	A wave describes a disturbance in a material medium [a variation in a physical field, displacement in water or changes in electric field].	Wave represents probability distribution of possible values to observe. [A wave function describes amplitudes, from which the probabilities of values measured are calculated].
State of matter	Continuous	Discrete and Continuous
Interference pattern	Appears as continuous pattern of distribution of brightness	The same pattern emerges from the distribution of numerous singular spots
Values of an observable	An observable has a definite value at a given time, whether or not it is measured.	The quantum state determines the probabilities of possible measurement outcomes. An observable may lack a definite value before measurement and acquire a definite value upon measurement.
The status of “unknown value” of an observable	the value exists but we (who measure) don’t know it. [epistemic uncertainty, ignorance to be overcome]	the value does *not* exist prior to measurement though the distribution of possible value is known [ontic indeterminacy, ignorance not possible to overcome]
Schrödinger’s cat — the meaning	The cat is either alive or dead whether it is known or not to the observer / who might have probable expectation	Since the cat cannot combine the states of being alive and dead, a real cat is not a subject for quantum description
Correlation between two events	The knowledge of one of the events is certain and it determines the value of the other event (classical telegraph) [locality coexist with causality]	The state of one of the entangled particles is random. The state of the other one is correlated with the first (quantum telegraph is impossible) [locality and causality split]
Kind of matter	Single	Dual (fermions and bosons)
State occupation	Limited only in volume	Pauli exclusion principle, Bose condensate

Instructions: Identify criteria of difference between classical and quantum objects. For each criterion, specify the difference..		
Confinement	Possible	Impossible, Tunnelling

Table 2

b Similarities between classical and quantum physics[5] (Examples of filling. Square brackets mark the topics of the observed discussions.)

Instructions: Identify criteria of similarity between classical and quantum objects. For each criterion, specify the similarity.		
Subject for comparison	Classical physics	Quantum physics
States of material objects	Numerical characteristics (though different) of physical states	
Measurement	Numerical measurement of physical observables.	
Characteristics of state	Energy, momentum, rotational momentum	
Prediction	The kind of characteristics require appropriate apparatus of measurement. Measurement accuracy hold whether determined or probable. [QP does not imply that measurements are inaccurate.]	
Conservation laws	Energy, momentum, rotational momentum are conserved	
Mathematical description of waves	[In the linear regime], waves [and wave functions] obey the superposition and can exhibit interference.	
Theories relationship	Under parameter variation, the QT provides CT numerical results (complementary principle)	

The task was followed by a discussion in which these and other aspects were revisited and examined in terms of the relationship between the nucleus of each theory and the corresponding alternatives in the periphery. The teacher also explicitly identified the higher-order thinking involved in the comparison task, particularly the need to establish comparison criteria, that is, to identify the aspects of knowledge to be compared. This cognitively demanding process encourages learners to consider how the individual entries in the tables characterize each theory and contribute to appreciation of the conceptual content and structure, more meaningfully than viewing them as isolated within a single theory where they can be simply lost.

4.2. Copenhagen and Hidden Variables interpretations

After learning about entanglement and EPR, learners watched several videos explaining Bell's inequality and its experimental implications [44]. While watching, they completed a worksheet that challenged them with several questions: What problem did each presentation address? How did it explain the correlations between measurements on spatially separated systems? Whether and how could

experiment distinguish between the accounts? What did each of them able to predict, and what conclusions could be drawn from the experimental data?

The activity was followed by a discussion organized around four questions:

1. *What are the core assumptions of each considered account of entanglement, and how can they be situated within the nucleus–body–periphery structure?*

The quantum account describes the particles through a joint entangled state and predicts correlations that violate Bell's inequality. These *instant* correlations contradict local hidden-variable models which would imply faster-than-light communication. The assumption of local hidden-variable presents an alternative in QT and thus are ascribed to the DC periphery.

2. What are the goals of each account?

Both accounts seek to explain correlations between measurements on spatially separated objects. QT predicts correlations between the random results of measurement. Local hidden-variable models imply underlying variables preserving causality.

3. Why do we consider alternative explanations, and how do we choose between them?

The discussion considered the ability to predict experimental results competing accounts and the information transfer. Within the DC framework, this comparison addresses items of nucleus, body and periphery and promotes learners' understanding of both classical to quantum physics theories.

4. What is the implication of EPR phenomenon?

Experimental violations of Bell's inequality support the quantum predictions and rule out local hidden-variable explanations under the given assumptions, including the independence of measurement settings from the hidden variables [45, 46]. Possible to be rejected the hypothetic local hidden parameters account is ascribed to the periphery of the DC structure.

Together, the videos, worksheets, and discussions encourage learners to explicitly consider competing explanations and appreciate the experimental evidence in physics. They also encourage learners to reflect on the process of choosing between explanations, to consider construction of individual knowledge framed in a coherent theory.

4.3. Copenhagen and Many Worlds interpretations

Unlike the comparison between the accounts by QT and hidden-variables, the debate between the Copenhagen interpretation (CI) and the Many-World interpretation (MWI) was purely speculative, no experiment was addressed. These interpretations offer different accounts of QT with different core commitments concerning probability and measurement. After studying the canonic CI, the learners (students or teachers participating in a workshop) watched another video [47] introducing the MWI. They completed a worksheet, followed by a discussion organized around four questions:

1. *What are the core claims of the considered interpretations, and how could they be situated within the nucleus–body–periphery structure?*

CI and MWI employ wave functions and the superposition principle. Yet, within the former [20, 21], measurement produces a single outcome through the wave-function collapse with the probability determined by the Born rule. In MWI, however, the quantum state evolves deterministically without collapse. Measurement involve the tool and the system causing emergence independent branches of reality, each with one of possible outcomes. MWI seeks to account for Born-rule probabilities within this branching description, although their interpretation and justification remain debated (and discussed very briefly in the classroom). Within the DC framework, the contrasting commitments concerning collapse and branching can be examined as alternatives in the periphery of QT.

2. What was the explanatory goal of each interpretation?

MWi and Ci seek a coherent account of quantum phenomena, such as in the double-slit experiment, EPR experiment, and Mach–Zehnder interferometer. While the CI relates the measurement outcomes to the wave function collapse, MWI seeks to account for these phenomena using the same quantum dynamics for both the measured system and the measuring apparatus, without introducing a separate collapse rule.

3. Why do we consider alternative interpretations, and how do we evaluate them?

The discussion addressed the polyphony of possible scientific accounts, the role of alternatives in the knowledge production and the role of scientific method: the empirical justification, explanatory coherence, and simplicity. There is opportunity to mention Occam’s razor, to reveal the problematic nature of simplicity: fewer rules, commitments, presuppositions.

A possible reflection on the tentativeness of scientific knowledge may arise through the rhetoric questions regarding the future changes. They however may distinguish the empirically supported predictions of QT from unresolved questions and speculations revealing to the learners the scientific way to resolve uncertainty and prepare future exploration.

4. The comparison of different quantum interpretations.

The discussion may elevate other alternative interpretations learned in the course (Table 1). Learners considered the similar and different between the compared interpretations: CI and hidden variables; CI and MWI, the NOS aspects of contrasting assumptions and the availability of experimental tests that would distinguish between competing accounts of reality.

Though CI is a commonplace in teaching QT, our curriculum does not address the strict disciplinary content alone. We encourage learners to engage with the subject matter at two levels. The *first* addresses concepts and phenomena and distinguish between them. The concepts are usually provided by the nucleus (such are superposition and measurement, etc.) and relate them to correspondent phenomena in the body (such are the double-slit experiment, the Mach–Zehnder interferometer, etc.). The established hierarchy guides the construction of arguments in discussions and worksheet responses.

At the *second* level, QT is addressed as a whole. The learners are encouraged to reflect on how these concepts, phenomena, and interpretive commitments fit together into a coherent cluster of knowledge items — a fundamental theory of physics. The implied DC structure enriches this teaching-learning process through inclusion of alternatives: interpretations and accounts in other theories (mechanics, optics, electromagnetism), classical and quantum. Thus, enriched panoramic perspective becomes a means of examining how individual knowledge items are connected within QT, how the learners make sense of the theory that differs substantially from those previously studied, and how these elements are organized into a coherent conceptual structure.

5. Discussion

Teaching and learning QT is extraordinary, and it is unlike the teaching of any other theory in the school curriculum. The situation appears paradoxical: it is not enough that QT describes reality in blunt contradiction to common-sense expectations of how objects behave; it is not enough that it requires mathematical tools unavailable to school students—yet it is allotted only a tiny teaching slot of about 30 hours. The new vision of teaching QT projects on teaching other content-heavy, mathematically driven instruction of mechanics, electromagnetism, optics.

The suggested change in teaching QT replaces the treatment of a few introductory topics with the representation of the theory as a whole. The DC paradigm provides a way to achieve this through a hierarchical structure that distinguishes principles from phenomena, the nucleus from the body. Furthermore, DC elevates the discipline into a culture by introducing a comparative presentation of conceptions—showing how quantum and classical accounts coexist, diverge, and illuminate one another.

As we observed, several features of QT possess strong attractive potential for school students, stimulating engagement in class discussion and genuine curiosity— especially when the teacher addresses the co-existence of different theories and interpretations within the same theory. Similar

engagement we noticed in teacher training workshops. A central example is the revolutionary feature of non-locality together with preservation of causality. This far-from-trivial claim of QT has a profound impact on our worldview and cannot be overlooked [30, 31, 37, 48]. The discussion surrounding *entanglement* and the principle of locality—which forbids physical influence or information from traveling faster than light—naturally emerges when considering the EPR argument and the subsequent developments that created a diachronic debate in physics: Einstein—Bohr —Bohm —Bell—Aspect [45, 46, 49–52]. This arc vividly illustrates how scientific ideas evolve, how interpretations compete, and how empirical evidence reshapes our understanding of reality. In short, it became emblematic of the scientific method and as such can be used for teaching NOS.

In particular, EPR pointed to what they considered a problem within quantum theory; Bohr responded by insisting that no problem exists once the quantum description is applied to the system as a whole. Bohm later reformulated the EPR argument using spin, making it far more accessible for experimental testing. Bell then introduced a mathematical criterion enabling a decisive empirical test—a genuine *critical experiment*. Aspect subsequently carried out this test, providing experimental evidence for the nonlocality of QT, a result later confirmed by more advanced experiments. Following this profound shift in understanding, entanglement and nonlocality—while still preserving local causality—entered undergraduate-level QT textbooks by the end of the 20th century. What a great teaching narrative emerges: a sequence of conceptual challenges, theoretical refinements, and experimental breakthroughs revealing how quantum physics reshapes our picture of reality.

However, there is another aspect of the immense impact of nonlocality on our understanding of reality. Owing to its substantial practical importance, a new branch of quantum-based technology has emerged, including quantum computing, quantum cryptography, and quantum teleportation. This development launched—and quickly popularized—the claim of a *second quantum revolution* [53]. Although it indeed represents a revolution in our understanding, it is not a revolution in which a new theory replaces an older one; quantum theory itself remains intact.

What has changed is the landscape of applied physics—something that has happened more than once in the history of science. In the wake of classical mechanics, engineering mechanics emerged [54, 55]; within electromagnetism, quantum electronics developed following the invention of the transistor; and in astrophysics, major shifts in worldview followed new insights into the role of the observer, the modification of the cosmological equation, and detection of the gravitational waves—all within the theory of general relativity [56]. Each of these developments in the basic theory instigated specific applied physics to appear, and each time, a significant challenge to physics education naturally followed.

The question arises whether the new trend in applied physics—quantum-based high-tech technologies—should already be introduced in secondary-school education which traditionally tries to remain meaningful, and coherent for all students—beyond those who may eventually enter quantum-related fields. The pressure to adjust school curricula in order to produce a future quantum workforce is increasingly perceived and answered by education researchers [57, 58]. And how fast are such changes

expected? The answer from industry and policy circles is unequivocal: *as soon as possible*, and you decide how to do this effectively and without overwhelming students or distorting the broader aims of physics education — a challenge.

The study by Satanassi and colleagues [57] can be seen as a clear indication of this emerging reality. They produced a 20-hour tutorial that introduced the core content of entanglement, quantum teleportation, quantum information, and applied it as an extracurricular activity to a sample of 13th-grade students, volunteers, who had not previously encountered regular quantum instruction. They reported notable success: the students were able to engage with and appreciate the fascinating conceptual landscape of quantum physics. It definitely was intellectually stimulating for the students.

Both suggestions of this kind—applied quantum mechanics oriented toward quantum optics and related technologies—necessarily drop much of the foundational physics content of quantum theory that is relevant for electronics, chemistry, biology, and astrophysics. As such, they fit well the idea of an additional, specialized high-school-level course. Yet they also strengthen the view that a short, conceptually coherent introduction presenting quantum theory as a *fundamental* theory for the broader population of school students is unavoidable. This duality is instructive: while applied quantum courses can serve motivated students seeking applied physics literacy, the general curriculum still requires a compact but meaningful representation of QT as a foundational scientific framework—one that shapes modern physics across multiple domains.

A well-known Hellenistic parable tells of King Ptolemy, who wished to study geometry and asked Euclid to teach him. Ptolemy requested to begin with polyhedra—the subject of the thirteenth and final book of *Elements*. Euclid was perplexed and replied that he could not do so. When asked why, he answered that “there is no royal road to geometry.”

Of course, it is only an old parable, and it may not hold in modernity, yet it still provides meaningful warning to consider before doing radical changes. Omitting the basic introductory elements of quantum theory from the first encounter with it—however tempting it might be in light of modern needs—deserves careful consideration. In our view, even in our age of prevailing pragmatism and pressure to accelerate learning, foundational conceptual preparation remains essential for genuine understanding.

6. Conclusion

Given the strict constraints of school reality—both in instructional time and in the limited mathematical background of students—we introduced a special organization of the introductory course in quantum theory for secondary-school students: a 30-hour curriculum offering a primarily conceptual account supported by basic mathematical symbolism. The course emphasized QT as a *fundamental* physical theory, standing in parity and complementary correspondence with classical mechanics, electrodynamics, and optics, and possessing a triadic hierarchical structure aligned with the discipline-culture paradigm.

Our experimental implementation indicated that precisely the existing curricular constraints create a unique opportunity: they allow the introduction of a holistic view of the conceptual meaning of physics knowledge. Students can encounter physics as a family of fundamental theories, each offering a distinct yet coherent picture of the world, and all sharing characteristic features of the scientific method. In this way, teaching QT supports deeper understanding of physics not merely as a collection of topics, but as an integrated cultural enterprise.

Declarations

• No funding was received to assist with the preparation of this manuscript.

• All authors contributed to the study conception and design, material preparation, data collection and analysis. The first draft of the manuscript was written by Igal Galili. All authors commented on the previous version of the manuscript, read and approved the final manuscript.

• The authors declare that they have no conflicts of interest.

Author Contribution

• All authors contributed to the study conception and design, material preparation, data collection and analysis. The first draft of the manuscript was written by Igal Galili. All authors commented on the previous version of the manuscript, read and approved the final manuscript.

References

1. R. A. Serway, C. J. Moses, C. A. Moyer, *Modern Physics* (Saunders College, 1997)
2. P. A. Tipler, R. A. Llevellyn, *Modern Physics* (Freeman, 2012)
3. M. Born, *Atomic physics* (Hafner, 1962)
4. I. Galili, E. Goren, *Science & Education* (2023) https://doi.org/10.1007/s11191-022-00348-w.
5. H. K. E. Stadermann, E. van den Berg, M. J. Goedhart, *Physical Review Physics Education Research* (2019) https://doi.org/10.1103/PhysRevPhysEducRes.21.010130
6. L. Laudan, *Philosophy of Science* 48(1), 19–49 (1981)
7. D. J. Griffiths, *Introduction to Quantum Mechanics* (Prentice Hall,1995)
8. D. H. McIntyre, *Quantum mechanics: a paradigms approach* (Pearson, 2012)
9. A. Buzzell, T. J. Atherton, R. Barthelemy, *Physical Review Physics Education Research* (2025) https://doi.org/10.1103/PhysRevPhysEducRes.21.010102
10. S. Pollock, G. Passante, H. Sadaghiani, *American Journal of Physics* (2023) https://doi.org/10.1119/5.0109124

11. A. Donhauser, P. Bitzenbauer, L. Qerimi, S. Heusler, S. Küchemann, J. Kuhn, M. S. Ubben, *Physical Review Physics Education Research* (2024) https://doi.org/10.1103/PhysRevPhysEducRes.20.020601
12. K. Krijtenburg-Lewerissa, H. J. Pol, A. Brinkman, W. R. van Joolingen, *Physical review physics education research* (2017) https://doi.org/10.1103/PhysRevPhysEducRes.13.010109
13. M. Michelini, A. Stefanel, in The International Handbook of Physics Education Research: Learning Physics, ed. By M. F. Taşar, P. R. L. Heron (AIP Publishing, 2023), pp. 8-1-8–34.
14. R. Muller, H. Wiesner, *American Journal of Physics* (2002) https://doi.org/10.1119/1.1435346
15. G. Pospiech, in Teaching-Learning Contemporary Physics. Challenges in Physics Education, ed. By B Jarosievitz,.C. Sükösd (Springer, Cham, 2021) https://doi.org/10.1007/978-3-030-78720-2_4
16. M. Michelini, A. Stefanel, in Connecting research in physics education with teacher education, ed. By E. McLoughlin, J. Guisasola (ICPE Book, 2022), vol. 3 https://doi.org/10.5281/zenodo.5792968
17. Merzel, A., Weissman, E. Y., Katz, N., & Galili, I. *Physical Review Physics Education Research* (2024) https://doi.org/10.1103/PhysRevPhysEducRes.20.020134
18. M. Förster, C. Albert, G. Pospiech, *Physical Review Physics Education Research* (2026) https://doi.org/10.1103/zwh6-84p5
19. A. Merzel, P. Bitzenbauer, K. Krijtenburg-Lewerissa, *et al.*, European Physics Journal of Quantum Technology (2024) https://doi.org/10.1140/epjqt/s40507-024-00237-x
20. E. Y. Weissman, A. Merzel, N. Katz, I. Galili, Journal of Physics (2019) https://doi.org/10.1088/1742-6596/1287/1/012003
21. E. Weissman, A. Merzel, N. Katz, I. Galili, Journal of Physics (2021) https://doi.org/10.1088/1742-6596/1929/1/012051
22. I. Galili, *Science & Education* (2026) https://doi.org/10.1007/s11191-026-00766-0
23. M. Ubben, P. Bitzenbauer, *Frontiers in Quantum Science and Technology* 2, 1207619 (2023)
24. F. Hennig, K. Tóth, J. Veith, P. Bitzenbauer, *European Physic Journal. Quantum Technology* 11(1), 61 (2024)
25. G. Irzik, R. A. Nola, *Science & Education* (2011) https://doi.org/10.1007/s11191-010-9293-4
26. S. Erduran, Z. R. Dagher, in Reconceptualizing the Nature of Science for Science Education (Springer, Dordrecht, 2014), vol. 43 https://doi.org/10.1007/978-94-017-9057-4_1
27. M. Beller, *Quantum Dialogue: The Making of a Revolution* (University of Chicago Press, 1999)
28. M. Michelini, S. Faleti˘c, G. Pospiech, in Physics Teacher Education, Challenges in Physics Education, ed. By J. Borg Marks, P. Galea (Springer Nature, 2021) https://doi.org/10.1007/978-3-031-44312-1_6
29. E. Weissman, A. Merzel, N. Katz, I. Galili, MDPI Physics (2022) https://doi.org/10.3390/physics4040083
30. M. Bunge, Science & Education (2003) https://doi.org/10.1023/A:1025336332476
31. J. Bricmont, Making sense of quantum mechanics (Springer, 2016)

32. D. Bohm, *Physical Review* 85, 166–179; 180–193 (1952)
33. S. Goldstein, Bohmian mechanics, in *Stanford Encyclopedia of Philosophy*, ed. By E. N. Zalta (Stanford University 2001). https://plato.stanford.edu/archives/sum2004/entries/qm-bohm/stanford
34. A. Einstein, The letter to Solovin (The Jewish National and University Library, the Hebrew University of Jerusalem, 1952)
35. H. Reichenbach, Experience and prediction. (University of Chicago Press, 1938)
36. K. R. Popper, *The logic of scientific discovery* (Hutchinson, 1959)
37. M. Bunge, Science & Education (2012) https://doi.org/10.1007/s11191-011-9410-z
38. R. A. Healey, *Foundations of Physics* 52(4), 1–20 (2022)
39. P. A. Heelan, *Quantum mechanics and objectivity* (M. Nijhoff, 1965)
40. H. Poincare, *Science and Method* (Thomas Nelson, 1915)
41. A. Merzel, E.Y. Weissman, N. Katz, I. Galili, in Physics Teacher Education, ed. By J. Borg Marks, P. Galea, S. Gatt, D. Sands, Challenges in Physics Education (Springer, Cham, 2022) https://doi.org/10.1007/978-3-031-06193-6_12
42. S. Satanassi, S. Erduran, *Physical Review Physics Education Research* (2026) https://doi.org/10.1103/8sq2-zrr9
43. S. Levy, E. Bagno, H. Berger, B.-S. Eylon, in Physics education research conference proceedings (AAPT, Washington, DC, 2019) https://doi.org/10.1119/perc.2018.pr.Levy
44. https://; https://www.youtube.com/watch?v=JFozGfxmi8A https://www.youtube.com/watch?v=zcqZHYo7ONs
45. J. S. Bell, Physics, 1(3), 195–200 (1964) https://doi.org/10.1103/PhysicsPhysiqueFizika.1.195
46. Shalm, L. K., et al. *Physical Review Letters* (2015) https://doi.org/10.1103/PhysRevLett.115.250402
47. https://www.youtube.com/watch?v=kTXTPe3wahc
48. A. Hobson, Quantum Physics (arXiv:1901.02088 quant-ph, 2019) https://doi.org/10.48550/arXiv.1901.02088
49. A. Einstein, B. Podolsky, N. Rosen, *Physical Review* 47, 777–780 (1935)
50. N. Bohr, *Physical Review* 48(8), 696–702 (1935)
51. D. Bohm, *Quantum Theory* (Prentice-Hall, 1951)
52. A. Aspect, P. Grangier, G. Roger, *Physical Review Letters* (1982) https://doi.org/10.1103/PhysRevLett.49.91
53. J. P. Dowling, G. J. Milburn, Quantum Physics (arXiv:quant-ph/0206091 2002) https://doi.org/10.48550/arXiv.quant-ph/0206091
54. R. K. Bansal, A Textbook of Engineering Mechanics (Laxmi, 2016)
55. J. E. Boyd, Mechanics. A Textbook for engineers (Mac-Graw Hill, 1921)
56. E. R. Harrison, *Cosmology* (Cambridge University Press, 2000)

57. S. Satanassi, E. Ercolessi, O. Levrini, Physical Review Physics Education Research (2022) https://doi.org/10.1103/PhysRevPhysEducRes.18.010122
58. I. Koponen, A. Pajula, M. Nousiainen, *International Journal on Math, Science and Technology Education*, 10(1), 1. (2025)
59. https://journals.helsinki.fi/lumatb/article/view/2600

Footnotes

1. [1, 2] and numerous undergraduate textbooks of introductory physics include Modern Physics as their last chapters.
2. See especially for the aspect to objectivity.
3. Poincare [40, p. 129] put it this way: “Beside the future engineers are other less numerous pupils, destined in their turn to become teachers, and so they must go to the very root of the matter; a profound and exact knowledge of first principles is above all indispensable for them.”
4. Five last items in the table were added to illustrate the approach. They were not tried in the quoted experiment.
5. Angular momentum was mention only to teachers
6. Our experimental try suggests 30 hours in our system of 12 years long school. Some countries (e.g. Italy, Germany) enjoy the advantage of 13 years long schooling. The opportunities there are essentially better and a correspondent curriculum can be comparable in length to classical mechanics. However, the advantages of the DC structure remain valid.
7. Was it similar to the finally proved the Big Fermat theorem — a great progress, but no revolution in mathematics.
8. Unlike regular physics textbooks, in engineering mechanics, for example, the First Newton’s Law is replaced by the First Law of Euler, F = ma, and inertial forces are used as regular interactive forces without mentioning their observer dependence
9. e.g. Satanassi et al. [57] in Italy and Koponen et al. [58] in Finland