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Teaching quantum physics as a structured physics theory in high school

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Abstract. This study presents a new approach to teaching quantum physics in high-school physics courses facing the extremely deficient and fragmented treatment of quantum mechanics at present. The suggested curriculum adopts the paradigm of discipline-culture in representing physics knowledge. In accordance, the curriculum is structured in nucleus-body-periphery emphasizing the principles (nucleus), their illustration (body) and their contrast with the classical postulates (periphery). Thus, the proposed curriculum presents quantum physics as a structured physics theory, unlike most curricula in the world. The results of an experimental application show a positive impact on students’ conceptual knowledge and students’ nature-of-science understanding.

1. Introduction

Quantum Theory (QT) is one of the most important developments in modern physics. However, in Israel, the Advanced Placement physics curriculum of high schools is extremely short and includes only a few fragments from the historical dawn of the theory such as the photo-electric phenomenon, Bohr’s model and radioactivity. The situation in other countries is somewhat similar but the content varies. There is no universal curriculum. Assessment usually draws on using a few formulas in simple quantitative problems illustrating the theoretical instruction. Typically, teaching of modern physics scarcely represents QT as an essentially new world picture contrasting deeply with classical theory. Students miss the holistic picture and a structural hierarchical account of this fundamental theory of physics. School educators often justify this curricular approach by the special difficulties of mathematical (lack of tools) and conceptual (contradiction with "common sense") nature required in learning QT. Those are claimed to be beyond the abilities of high school students. What enhances the difficulty is very little time left in the curriculum (about 50 hours for all the matter-radiation unit in Israel). The apologists of such an approach (of superficially familiarizing with some features of modern physics) refer to the fact that university instruction of QT takes place during three or four semesters and uses advanced mathematical tools. Clearly, those who see school instruction as a simplified university conclude the impossibility of seriously learning QT in schools.

The context of high school education presumes an essentially different approach and goals aimed at acquisition of a sufficiently representative conceptual understanding of the ideas rather than a valid practical tool. Therefore, school instruction requires a different design matching the abilities of high school students. Such an approach is currently missing and presents a challenge for physics educators. Teaching QT in high school should display it as a physics theory of the world and strengthen that hitherto the students have already learned other basic theories, mechanics and electromagnetism, valid in certain
areas of physical parameters and context. Such an approach may replace the teaching of QT starting from classical concepts and then explaining the differences in the new theory [1].

This study produced a new curricular approach drawing on a novel theoretical framework and employing the symbolic formalism of Dirac for a simple quantum system never used before in school instruction. The new curriculum possesses the structure of discipline-culture (DC) in presenting a physics theory [2]. Its curricular application seeks cultural content knowledge of the subject matter on behalf of high school students [3],[4]. This study applied this perspective to quantum mechanics in order to represent it as a fundamental theory – QT.

In the course of the study, the basic principles of QT were determined basing on the relevant literature and interviews with physics professors. Experiments of illustrative nature were chosen. Teaching content of QT was contrasted with the corresponding accounts of classical mechanics and other alternative conceptions [5]. The suggested curriculum covers 50 hours of class teaching. It is aimed at establishing a valid introductory representation of QT at schools. The advanced mathematical structure and several activities were adjusted to the level of high school students. A limited experimental application of the new curriculum was carried out in several teaching samples, and this paper presents some of the experimental results, their findings and the assessed impact of the applied teaching-learning sequence on the content understanding of quantum physics by students.

This study deals also with characterizing the nature of scientific knowledge (NOS) in general. The knowledge of students was probed prior to instruction and after it. The data provides information with respect to the learners’ views on the NOS and scientific method. The impact of the new instruction on the pertinent knowledge is discussed with respect to its implications to physics curricula in schools.

2. Background

An extensive review of QT curricula (at school level) revealed a spectrum of approaches to teaching the subject. Research reports a variety of problems of knowledge representation as well as pitfalls of students' understanding of the subject matter [6]. Introductory university courses usually proceed through displaying the historical consolidation of QT and introduce its mathematical account in a yearlong course (e.g. [7],[8]). In contrast, school educators face strong constraints. Even a descriptive historical display is impractical for the lack of time and the required background in electro- and thermodynamics as learned at high school on our days. Schools thus limit teaching to certain topics that look feasible to deal with at school, trying to depict the features of quantum physics as emerged in the beginning of the 20th century (e.g. [9]).

In reality, however, even such approach is abandoned. School educators selected even a smaller subset of the big picture fitting the short timeslot reserved. The selections created a variety of content in contrast to the teaching, say, the classical mechanics possessing traditional components. Thus, Petri and Niedderer [10] argued for semi qualitative fragmentary understanding of electron behavior in atoms using a classical analogy with string behavior. In contrast, others introduced the perspective of ensembles of elementary particles [11],[12] and omit classical analogies [13]. Still others went straight to the advanced account of the path integral approach to represent quantum behavior qualitatively [14].

Those approaches applied in school teaching of quantum remain highly fragmentary (lacking holistic organization of knowledge elements) without ambition to represent a new theory; even when educators have much more time of instruction, as available in Germany and Italy (13th grade), while others have 12 years of school (Israel, US) or even less (Russia). Furthermore, QT addresses the subject of the micro-world where of concepts of wave and particle as used in classical physics are essentially changed. The basic quantum object is fundamentally different in nature even if using the same terminology. Therefore, QT requires a new notion for the fundamental object – 'quanton' [15]. Quanton possesses properties of a particle and features of wave nature manifested in results detected in experimental settings of the macro-world. Quantum behavior contrasts the behavior of objects in the perspective of classical physics, mechanics and electrodynamics. It is therefore perceived as very strangely contradicting common sense. This causes inadequate use of vocabulary such as tunnelling, collapse, motion, wave (wave function) which change their meaning and
are used in the sense restricted to the specific reality of the micro-world. Following this complexity, the novice students often show naive mixing of wave and particle aspects in various ways contradictory in the macro-world but still incorrect in micro world either – misconceptions [16].

School teaching approaches to QT are known for lacking an inclusive hierarchically organized structure displaying certain fundamental principles. Such teaching approaches do not consider a “big picture” which would define the wave function, quantum states and other fundamental concepts [17]. This study tries to fill the lacuna in researches on teaching quantum physics in several aspects. It developed an innovative curriculum structured in the DC-paradigm [2].

It is true that though taught in volume, mechanics and electromagnetism parts of the curricula were not organized in a theory structure either. Yet, facing the extreme constraints in the required presentation of QT, the introduction of the DC structure seems even more required. Within this framework of representation of a physics theory, its knowledge elements are hierarchically arranged in terms of the nucleus (the basic principles) and body (the knowledge elements subdued to the nucleus) (Fig. 1). This dual disciplinary structure is extended to the periphery, which addresses the major alternatives to the nucleus on behalf of other theories, conceptions, ideas and experience. All together, they present the triadic organization. Structured in the triadic structure in terms of nucleus-body-periphery a theory is termed discipline-culture (DC).

**Figure 1. Discipline-culture structure**

This study adopted the DC-based approach to any physics theory and developed it in construction of a new curriculum for teaching QT. In accordance, there appeared the basic principles of QT, the corresponding illustrative phenomena and experiments, and the rival corresponding ideas/accounts either from classical physics or early interpretations of quantum phenomena. All these contents were provided in qualitative form in order to fit the constraints of school reality. Yet, we did not completely neglect the quantitative-computational approach. This became possible using the formalism of Dirac notation of state which reduced the mathematics to be feasible for introductory learning at school. The new curriculum avoids using complex numbers and differential equations but still presents the major ideas of QT in their conceptual sense.

It is plausible to consider that restructuring physics knowledge within the new approach of teaching should cause interest and curiosity among the students who were never instructed that way before. They would realize that physics is comprised of fundamental theories possessing hierarchical structure. This would imply awareness of different elements of such knowledge – theories, principles, laws, models, experiments etc., different by nature, and somehow related hierarchically. In fact, this subject is investigated in physics teaching research where it is in focus of a hot discourse between opposite perspectives ([18],[19],[20],[21]). The debate addresses the common confusion of students and incompetence of teachers totally ignoring the features of nature of science (NOS) and its method. Our approach, with QT structured in the triadic manner, comparing between quantum and classical accounts with respect to their validity reveals new features of epistemological nature on behalf of secondary school students and their teachers.
3. The research – empirical framework

3.1 Goals and structure
The goal of this study is to examine the possibility of an alternative teaching of modern physics in high school. The research was done in Israel, but to the best of our knowledge the problem of representation of this knowledge in high schools is relevant and innovative universally. Modern physics is typically taught at grade 12 of high school. Facing an inadequate curriculum obliged the development of a full alternative curriculum addressing quantum theory within the chosen DC approach. The product should be applied to a representative sample of students and be presented to teachers. These empirical steps should explore and assess students’ understanding, their conceptions regarding the subject matter and epistemology (NOS).

In accordance, the study incorporated two parts – a theoretical preparatory stage and empirical application. The first part included the construction of the curriculum – identifying the nucleus of quantum physics, choosing the representative examples (body) and the corresponding alternative understandings (periphery). The first part included a research literature review and interviews with experts – a group of university physics professors. Based on that, the content and teaching aids were developed. In the second part of the study, experimental teaching at school was applied and assessed. In addition, a special workshop was performed with a group of school teachers to familiarize them with the new curriculum and probe their perception and views.

3.2 Population and samples
In the first part we explored the views of experts – physics university professors. The sample incorporated 5 professors selected by their direct involvement with QT in their research. In parallel, a sample of 8 textbooks in modern physics for teaching at college level (approximately corresponds to our high school physics matriculate at the highest level) was explored. The sample was selected for popularity of use at the college level of instruction.

In the experimental study addressed both students and teachers. The sample of students included four groups of 12th grade (AP level) in a regular urban school of Jerusalem: 15 students (E1), 6 students (E2), 14 students (E3) and 17 students (E4). However, most of the relevant data was taken from groups E3 and E4, whereas the earlier ones were more used as pedagogical and research pilots. The teacher sample included 16 individuals active in different schools across the country who participated in a workshop aimed at exposing these teachers to teaching methods of QT in high school. Yet, our results regarding teachers is beyond the scope of this report.

3.3 Pedagogical approach
Teaching was performed in regular high school classes during two successive study years. The style of teaching actively involved the students in the course of the lecture. That was possible due to the relatively small groups usually enrolled in physics classes. Specially developed activities and teaching aids were applied. The appropriate assessment followed the teaching guiding the ongoing changes in teaching materials and providing the students with a feeling of continuous support and control.

3.4 Research questions
The first part of the study sought the answers to the following questions (appropriate for learning by high school students):

1) What is the nucleus of QT?
2) What elements of QT can effectively illustrate the principles of the nucleus (body)\
3) What elements of knowledge appeared as alternative to the considered elements of the nucleus (the periphery of QT)\
4) What mathematically relevant (to QT) tools can be taught in high-school? Can Dirac notation be appropriate for the goals of the high school course of QT?\
5) Were the developed teaching aids effective in supporting the learning process?
6) Which assessment tools (questionnaires) are appropriate and sufficiently informative for the impact of the developed curriculum on students’ knowledge?

The second part of the study focused on the following questions:

7) What are the content understandings of the students after the teaching?
8) What are the students’ difficulties and conceptions in learning QT?
9) What is the epistemological impact of teaching on students’ awareness and understanding of the features of NOS?

3.5 Research tools

The research tools in the first part of the study included interviews and a literature review. In the second part, active teaching was followed up with observations by the researcher and audio recording of all teaching sessions.

Students’ knowledge regarding the pertinent features of NOS was probed prior and after teaching, while their knowledge on the subject matter was tested only following the teaching. The questionnaires comprised open questions. The teaching expanded to home tasks (activities) evaluated in the regular feedback procedure. One group of the sample was tested in the ability of near transfer of the developed skill to a novel context. An additional tool was semi-structured interviews with students selected (n=8) in accordance with the teacher’s recommendations. The data was collected also from the students' activities, tests and homework.

As a control group the study employed a class 12th graders who studied the “standard curriculum” (waves, optics, issues in “modern” physics) mentioned earlier. The other control group used was of university students at the end of the second year who completed their first course in quantum mechanics.

Recruiting control groups faced difficulties. Firstly, in recent years, changes introduced by the Ministry of Education, the “standard curriculum”, modern physics was excluded from the external matriculate examination which significantly decreased the weight of the subject in school teaching and thus made difficult to find a group for a fair comparison. Secondly, the university students only generate indicative information as they faced essentially different curriculum. The limited validity of control groups did not devaluate our pre-post comparison within the research sample.

The data collected from the questionnaires, activities and interviews were analyzed using qualitative research methods, based on the "grounded theory" approach [22],[23].

With regard to the teachers, pre- and post- questionnaires were conducted aimed at the understanding of the pertinent QT content. An evaluative scale was built to characterize the understanding.

3.6 Validity and reliability

In the preliminary study, the research validity drew on the selection of candidates for their high academic expertise and known pedagogical credit. The validity was further fortified with triangulation of the various resources of information: experts’ views, the published researches of teaching modern physics, popular textbooks, and the experience accumulated in pilot teaching. The open type of the questions used in the assessment excluded guessing induced by question content. The assessment included an especially reliable tool of checking students’ understanding by including the context requiring a near transfer of knowledge.

The study considered the content of eight popular textbooks with a strong tradition of teaching over the past few decades [8],[9],[24],[25],[26],[27],[28],[29].

We verified the validity of the questions in interviews and questionnaires by consulting with the previous studies, supervisors and colleagues. The claim of reliability of the research draws on the regular conditions in the classrooms, organic teachers, homework and exams performed as a routine. Several classes of similar population were involved. The classes were of regular size and average level for physics students. The students interviewed represented students at different levels of achievements drawing on teachers’ knowledge.
4. Theoretical part of the research – curriculum development

4.1 The curriculum
Following the analysis of the textbooks sample and experts’ interviews we elicited a set of the basic principles of quantum physics, sufficiently representative and assumed to correspond to the abilities to high school students. Pedagogical considerations have led us in choosing illustrative examples and applications, as well as alternative understandings.

The produced curriculum was organized according to the DC structure, and its content is represented in Table 1. We did not have enough time for the whole program, therefore we omitted the parts in gray font.

| Nucleus | Body | Periphery |
|---------|------|-----------|
| Particle-wave duality | Einstein account of photoelectric phenomenon | Classical waves of light and matter |
| Light duality | Thomson Jr. Electron diffraction | Light interference in double slit experiment (Young) |
| Matter duality (de Broglie) | Double slit experiment with light | Electrons passing through double-slit screen |
| Quantum particle – Quanton | Double slit experiment with electrons | |
| | Compton scattering | |
| Physical state – basis states and compound states | Schrödinger’s cat thought experiment | Classical state (x, p), motion, trajectory |
| Principle of superposition of states | Stern-Gerlach two-state system account | Classical determinism and uncertainty (Heisenberg initial interpretation of uncertainty) |
| Wave function, probability and measurement | Mach-Zehnder interferometer | Schrödinger matter waves |
| Uncertainty (indeterminacy) principle | Heisenberg position-momentum indeterminacy | Momentum and energy conservation |
| | Dirac symbolic notation of states | Bohr model |
| | Wave function in Dirac notations | |
| | Measurement in Dirac notation | |
| Operators of physical observables and equation of state (Schrödinger equation) | Schrödinger equation (symbolic form – Dirac notations) | Physical quantities and the equation of motion |
| Transition between states | Tunneling (Radioactivity) | Potential well, State stability |
| Fermions and bosons | Atomic structure and the Periodic Table of elements | Matter particles, single type of mass |
| Pauli principle | Photons and Laser | |
| Nonlocality | EPR thought experiment and Bohm modification for photons | Locality principle |
| Quantum entanglement | Bell inequality and Aspect experiment | Hidden variables theory |

4.2 Teaching aids and assessment tools
A special booklet was developed to represent the content of the new course, and it was used by the students throughout the experimental teaching. The book specified the affiliation of knowledge elements in the triadic structure as presented in Table 1. Teaching aids and assessment tools have been developed, including computerized activities and references to other resources.

4.3 The mathematical framework
One of the central innovations of this study in QT representation for high school students was the mathematical framework based on Dirac notation. Its pedagogical importance cannot be overestimated. It provided a very simple symbolism avowing the explicit use of any mathematical symbol leaving the
major idea of quantum formalism represented but not specified. Thus, while the numerous attempts to teach the Schrödinger equation proved its inappropriateness to school curriculum, in Dirac notations, it became clear and meaningful.

5. The teaching experiment
The experimental teaching presented a fragment of 30 hours of the full curriculum to fit the available time slot in school schedule in the currently adopted extent. The activities kept the students involved through the whole class period and allowed collection of students’ views. At the end of the program, the teachers administered an exam including conceptual and computational questions in order to evaluate the conceptual understanding and the ability of computational account of simple problems including the questions required knowledge transfer. In the following, 8 students were interviewed.
During the second year of experimental teaching, a special workshop for physics teachers was performed (24 hours). The new curriculum was presented and discussed in the perspectives of content and pedagogy. The teachers were asked to respond to pre- and post- questionnaires.

6. Results
6.1 Students (representative examples)
1. After learning 33 students faced the question regarding momentum and the problem of its definition as \( p = mv = m \cdot \frac{\Delta x}{\Delta t} \). The obtained dispersion of the answers included one third reasoned by x-p uncertainty as excluding the classical definition, another third pointed to the need to expand the definition \( p = \frac{\hbar}{\lambda} \) within the wave-matter unification and the rest (third) failed.
2. The teaching involved discussing wave functions representing superposition (using Dirac notation) and allowing to compute probability of each basis state. The question asked whether the expression \( |\psi\rangle = \frac{1}{2}|a\rangle + \frac{\sqrt{3}}{2}|b\rangle \) represents a wave. Most of students responded positively, indicating the understanding of waviness in quantum physics.
3. Most of the students of E3 and E4 groups showed understanding of the meaning of cross product \( \langle \psi | \varphi \rangle \) in eigenstates, orthogonal states and superposition states, calculate and interpret its value.
4. Seeking reliable evidence for students' understanding a special question addressed the Mach-Zehnder interferometer (Fig. 2) while it was not addressed in teaching (near-transfer understanding) (E3 and E4 groups).

In the class, the students learned about the two-slit experiment with and without a detector in one slit. Within the test, students were asked about the output from a Mach-Zehnder interferometer if a single photon was sent through it with or without measuring in one of the two pathways. They were asked to make and compare quantum and classical accounts of the experiment.
24 out of 30 students (80%) succeeded to correctly predict constructive or destructive interference. Of these, 20 students (67%) used superposition of states in their explanations, indicating a deeper understanding. In the scenario with the detector, 26 students (87%) predicted lack of interference, 25 of them used correctly the wave function collapse as a part of their explanation (deep understanding) (Fig. 3).
Figure 3. Students' predictions of MZ interferometer

Indicatively, while 20 students explained the existence of interference by superposition in the interferometer, only 9 of them mentioned superposition when asked about the basic principles of quantum physics. Only 3 of those who explained the lack of interference due to the collapse of the wave function, mentioned it as one of the basic principles. This disparity indicated the preference of contextual understanding of a principle (body knowledge) over considering it in general context of nucleus knowledge.

Along with that, we reviewed a number of difficulties and misconceptions. For example, for some students it was difficult to understand that the wave function is not local, thus, some students incorrectly considered wave function collapse only in one path rather than in the whole interferometer. Other students understood the probability in the context of many electrons, not in the context of the single particle [30]. However, none of our students showed erroneous understanding of particle wavity as following a wavy trajectory, which was reported by others as a popular confusion [31].

6.2 NOS perception of students and teachers

Teaching of quantum physics by the DC approach has helped students in knowledge organization. Students demonstrated good ability in organizing their knowledge, both in quantum physics which they learned in this approach, and in the classical mechanics they learned in the standard approach. However, it was evident that their internalization of nucleus-body-periphery conceptualization did not always imply correct affiliation of specific items of knowledge. This is however was secondary and reflects, for instance, possible confusion of fundamental (basic) and important.

The results of the study include a common confusion of the students in distinguishing and clearly understanding commonly used concepts such as theory, laws, models, area of validity, principles, concept definition, and experiment. This terminology is usually used by students intuitively and when asked for clarification became a subject of an intuitive account, often merely naive. Moreover, students showed a generalized view that physics presents a merely tentative knowledge: indeed, classical physics appeared to be inaccurate and was replaced with quantum physics.

The teaching of quantum physics in the DC approach presented QT as a hierarchical physics theory. This structure is valid not only for quantum theory, but also for other theories learned prior in the physics course. The important finding, thus, was that students come out of a physics class without a clear view on the nature of knowledge they had acquired, confused when asked about this commonplace subject in general context. This is manifested in inconsistencies, inappropriate using of basic terms, and misunderstanding of the questions. The teaching experiment succeeded only partially in improving this situation but it heralded the important lacuna in the current physics education.

Lacking direct instruction on the NOS subject, most of the students however did not believe that scientific claims, in their essence, depend on researchers' beliefs (the objectivity of science). Some students stated the correctness of scientific claims in certain areas of validity, while other merely claimed scientific knowledge being tentative, inaccurate and a subject for change. The experimental teaching of QT in the DC framework of curriculum partially changed the distribution of the views in favor of the former. The study, in its declared scope and method does not claim a significant change in that aspect.
The evidence provided by physics teachers with regard to the subject of NOS in school teaching was threefold. The teachers unanimously stated the importance of this aspect of physics knowledge and its relevance to the introductory teaching of science. Yet, they mentioned that they never faced such questions in any assessment or teaching materials in their experience including their teacher training. Finally, they expressed uncertainty whether this material should be included as a separate unit of instruction or infused in an ongoing basis in regular instruction.

7. Discussion and conclusion
This study is going against the trend of the system of school education to significantly reduce the status, extent and the time devoted to QT in high schools. In contrast, the study testifies that being arranged in a different structure and possessing different content, teaching QT is not only possible, but presents a necessity. This is in light of the fact that the great majority of school students after graduation will never proceed to a more advanced learning of physics which is however required as an increasing need in order to manage in the modern hi-tech saturated society.

This study is innovative in both the curricular structure and its content. It shows that teaching modern physics in the DC approach enables the construction of a curriculum that meaningfully represents QT creating a holistic view on this fundamental theory. In contrast to the previous attempts of teaching QT, which often included the presentation of certain phenomena and experiments, as detached from the whole set of principles and ignoring the contrast to the principles in the foundation of other fundamental theories, this study grounded students' understanding in a more inclusive – cultural – perspective of physics knowledge. Moreover, it employed not merely conceptual account but included using a specific mathematical account employing the symbolic notation of Dirac. That allowed overcoming the extremely important obstacle of lacking sufficient mathematical tools. Although lacking the ability to solve standard problems of the university introductory course, the school course of this kind does equip its students with a meaningful picture of QT and ability to answer relevant questions and solve certain problems of a conceptual kind. The study revealed to the student the basic features of the quantum world related to measurement, probability, wave function, basic states, locality, etc. The study stated the remedy of some popular misconceptions of students which may be included in the periphery of the theory and considered in teaching-learning sequences.

The subject of NOS presents a hot debate in science education. Lederman [19] and Galili [21] presented disparate visions on this subject. The study addressed two major points in that debate. Lederman claimed that scientific knowledge, owing to scientists’ theoretical commitments, beliefs, previous knowledge, training experiences, and expectations, is “unavoidably subjective”. Galili, in contrast, asserted that scientific knowledge, as the collective knowledge of science community is essentially independent of personal will and values, thus stating its objective meaning. Furthermore, while Lederman stated that all scientific knowledge is tentative and presents a subject for change, Galili stated that the items of scientific knowledge vary in the range from certain (in a particular area of validity) to hypothetic, subject of further investigation. In that regard, he pointed to the confusion between the status of knowledge as gnosis – the ultimate all-inclusive truth about nature which might be considered in philosophy and religion – and episteme (the rational, experimentally verified self-corrected knowledge constructed using scientific methodology) the subject of natural science. Students’ confusion in this aspect of knowledge was detected in this study which did not include its explicit teaching.

The study documented confusion among students with regard to the status and nature of physics knowledge components – theories, laws, principles, models, experimental evidence, etc. The presentation of quantum physics content as a physical theory within the DC approach had only partially succeeded in improving this situation by emphasizing the structure of knowledge. The study output suggests a radical change as required in curricular design and teacher training courses by inclusion of new content. Such a change is beyond providing explanation “what is a model?” of quantum physics, but considers the status of knowledge items and methods as well as its specific advantages and areas of validity. Furthermore, the study points to the need of revisiting the structure and content of teaching
other parts of the school curriculum such as classical mechanics. When content was addressed in the experimental design of DC based teaching certain deficiencies were revealed in that regard too. Altogether, the results of the study support the possibility of teaching QT in high school in light of its necessity.

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