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# EFFECTIVENESS OF INTEGRATION OF NEW ICTS IN TEACHING/LEARNING OF QUANTUM CONCEPTS

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**Abstract-** The present work is a bibliographic synthesis starting from studies that have identified the different difficulties encountered in teaching/learning quantum mechanics and their causes, which prompt other researchers to suggest several innovations to overcome these difficulties. Therefore, studies that have integrated and evaluated different information and communication tools in the teaching/learning of quantum mechanics have been identified and categorized, including visualization tools, simulations, animations, programming, educational games, cartoons, MOOCs, virtual laboratories, and platforms. A reflection was made to evaluate the effectiveness of integrating these different innovations in learning quantum concepts. Thus, many pre-test and post-test results and the results of the students who integrated into the projects of innovation and those who not integrated into the project, show that there is a growing development of understanding of different concepts related to quantum mechanics. Furthermore, others studies have shown that integrating these tools motivates and engages learners in active learning.

**Keywords:** ICTs, Quantum Concepts, Teaching/Learning, Simulation, Programming, E-Learning, MOOCs.

## 1. INTRODUCTION

The last decades in the field of quantum mechanics education research that aims to improve the learning of quantum mechanics, several types of research appeared, firstly focused on identifying the difficulties and misconceptions of the students towards quantum concepts, using quantitative investigations [1, 2, 3], the categorization and understanding of these representations and MOOCs that present essential tools in teaching/learning in distance.

Finally, several projects have evaluated the integration of these new ICTs in the teaching/learning of quantum mechanics and have shown through different and difficulties was done using qualitative investigations These researches recommend that quantum concepts are too abstract, counterintuitive, far from the learner's daily life, with a complex mathematical formalism, and are different from classical paradigms, which make the students demotivated and do not engage in active learning, and push them to formulate misconceptions.

Therefore, to make learning active and to motivate students to engage in learning effectively, several researchers propose the integration of new information and communication technologies (ICTs) such as: visualization tools, programming, games, virtual experimentation, and E-learning. Indeed, according to the constructivist, the learner constructs his significant knowledge by himself, so visualization tools facilitate the task of knowledge construction by allowing the intuition to abstract concepts; on the other hand, simulation interactivity allows him to detect the different parameters on which the concept should be learned. Furthermore, research in neuro-learning has shown the relationship between visualization and learning.

The use of programming minimizes the use of mathematics and devoting time to visualize the results of programming. Games are another motivating and engaging factor through play, the learner builds conceptions while playing. On the other hand, some researchers [4] have proposed cartoons to bring the foundational ideas of quantum mechanics closer. Moreover, virtual labs are an excellent alternative compared to real labs, which are characterized by many limitations; they are an indispensable tool in distance learning, and they play an essential role in understanding abstract and counterintuitive concepts. The Covid 19 containment period has obliged the users to use platforms tests that integrating these innovative tools has enhanced the understanding of quantum concepts.

Therefore, through this work, we try to answer the following questions:

- What are the different methods used to identify and categorize difficulties in teaching/learning quantum concepts?
- What are the causes of these difficulties?
- What types of new ICTs have been used in the teaching/learning of quantum mechanics to improve the learning of quantum concepts?
- Does the integration of these new information and communication technologies improve the motivation and engagement of students in active learning?
- Do learners achieve any progress about the understanding of the quantum concepts by using the ICT?

## 2. MATERIALS AND METHODS

The methodology followed in this bibliographic synthesis has been done as follows. First, we started with previous studies which identified and categorized the different difficulties of teaching/learning quantum mechanics using quantitative and qualitative methods. Then we have synthesized different research studies that have suggested different innovations in teaching/learning quantum mechanics using ICTs. Finally, a synthesis of studies that have evaluated the effectiveness of these new technologies has been already done by researchers.

The research of these studies was done by using scientific and academic search engines, such as Refseek, Google Scholar, and by scanning databases containing scientific productions (articles, books, ...), such as CAIRN, JSTOR, Science Direct, Scopus, Springer Link, Web of Science, by using my institutional email which allows me the access to the various bases. The search was done by combining the word learning quantum mechanics with misconceptions, teaching/learning, simulations, programming, games, cartoons, virtual lab, and ICTs, while using the Booleans.

After the collection of articles, we have highlighted those that appeared in the period from 1996 to 2021, except for the articles that justify the theoretical framework of the study, such as Vygotsky's and Piaget's articles that clarify the learning theories appeared in a later date, and studies that have investigated the difficulties of teaching/learning quantum mechanics.

## 3. RESULTS AND DISCUSSION

### 3.1. Identification of Difficulties in Teaching /Learning Quantum Mechanics

In the field of quantum mechanics research, the first studies focused on identifying difficulties in teaching/learning quantum concepts and misconceptions, the identification of difficulties was conducted by these researches based on quantitative methods of investigation while using reliable and valid tools of investigation. Thus, in this context, several researchers have developed investigative tools such as QMCSQ (Quantum Mechanics Conceptual Survey Questionnaire) [2], QMFPS (quantum mechanics formalism and postulate survey) [3]. These investigation tools are generally in the form of QCM and or Open-Ended Questions, and they are tested for reliability by statistical tests such as alpha Cronbach's index, $KR20$, $KR21$, biserial discrimination index, which show the consistency of the tool, the validation of these tools is declared by teachers of quantum mechanics who have accumulated experience in teaching quantum mechanics. To understand these difficulties and misconceptions, other researchers have used qualitative methods using interviews, video recordings, and discussions.

These quantitative and qualitative investigations have shown that the causes of these difficulties in learning quantum concepts among learners are diverse, difficulties related to the nature of quantum concepts that are counterintuitive, too abstract, far from the daily life, difficulties with the persistence of classical paradigms, difficulties due to teaching practices, and difficulties related to the use of mathematics, which pushes learners to formulate misconceptions.

### 3.2. Integration of new ICTs in the Teaching/Learning of Quantum Mechanics

The various investigations on conceptual understanding in quantum mechanics show that students find the quantum concepts difficult to understand; so, they are demotivated and do not engage in learning. In light of these results, several studies suggest the use of new technologies, programming, simulations, virtual experimentation, cartoons, games, etc., which are new technologies that get the learning of quantum mechanics effectively.

#### 3.2.1. Computer Simulations

Visualization plays an essential role in learning, an active process centered on the learner in which the students themselves construct meaningful learning. Research has highlighted the benefits of visualization in the development of scientific understanding by providing opportunities for students to make connections with preexisting knowledge structures and new knowledge, on the other hand, visualization is an important part in learning. Thus, the use of simulation and visualization is beneficial in learning quantum concepts that are always too abstract and counterintuitive. In addition, quantum phenomena are inaccessible to our senses at the subatomic scale. On the other hand, visualization tools and interactive simulations allow learners to engage in an active learning process to build correct conceptions about quantum concepts. Table 1 shows the different advantages of integrating simulations in teaching/learning quantum concepts.

Then several researchers to contribute to the improvement of the understanding of quantum concepts that are too abstract to be understood have developed simulation projects such as PhET [7], QuILTs [6], QuVis [5], Quantum Composer [10]. these projects have proposed a series of simulations that have proven their effectiveness in improving the learning of quantum concepts. Figure 1 shows a Phet simulation that illustrates the photoelectric effect; the learner discovers the corpuscular aspect of light by manipulating the simulation.

Table 1. Advantages of simulations in learning quantum mechanics

| Benefits of using simulations in teaching/learning quantum concepts | Authors |
|---|---|
| Animations aim to help students build mental representations of abstract and counterintuitive quantum mechanics. | [ 5, 6, 7] |
| Create an active learning environment by manipulating interactive simulations which allow students to confront their misconceptions. | [6, 8, 9] |
| Support the learning and teaching of quantum mechanics through the accompanying activities. | [5] |
| Keep students actively motivated and engaged in the learning process. | [8] |
| Simulate experiences that are sometimes difficult to realize in reality, such as the Photoelectric effect, Stern Gerlach, Mach Zender. | [1] |
| Simulations allow us to visualize the concepts and phenomena that evolve with time, the evolution of a quantum state, passage of a wave packet in a potential barrier, the evolution of a particle in a potential well | [10] |
| Use visualizations and simulations of phenomena that cannot be experienced directly | [11] |
| Simulating the concepts that require 3D visualization | [12] |

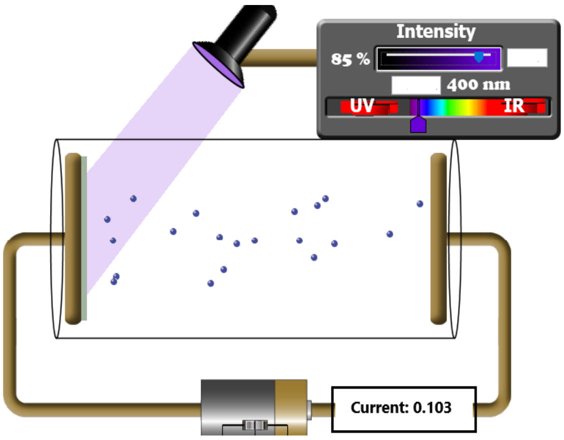
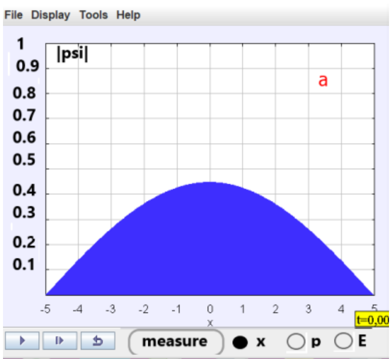



Figure 1. Phet Simulation of photo electric's experiment [7]

One of the QuILTs simulations, we quote the following simulation which shows that for a stationary state, the measurement of the position reduces the state of the particle into a proper state of the position operator, which is a delta function.

The Table 2 shows the different simulation projects that have been tested and proven to be effective in improving learning quantum mechanics.



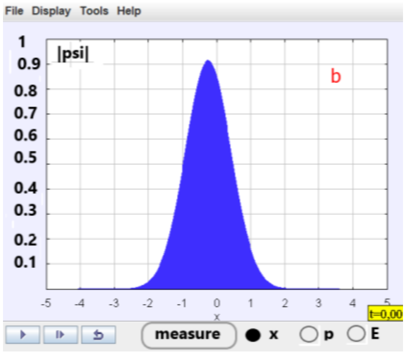




Figure 2. QuILTs measurement simulation, (a) before the position measurement and (b) after the position measurement [9]

Table 2. Different simulation's projects

| Projects | Authors | Language of development |
|---|---|---|
| Phet interactive simulations phet.colorado.edu | K. Perkins, C. Wieman and their Phet team https://phet .colorado.edu/en/about/team | HTML5, JAVA, CheerpJ, FLASH |
| QuILTs www.physport.org/curr icula/quilts | Singh, Christian, Belloni and PER team at the University of Pittsburgh USA | java |
| Physlet Quantum Physics: Introduction | Mario Belloni, Wolfgang Christian, Anne J. Cox | Java applets, JavaScript |
| QuVis | Antje Kohnle's team in university St Andrews | Adobe Flash, Mathematica |
| Quantum composer https://www.quatomic. com/composer/ | Jacob Friis Sherson's teamhttps://www.quatomic .com/about/ | C++ |
| http://ressources.univle mans.fr/AccesLibre/U M/Pedago/physique/02 /mndivers.html | Jean-Jacques ROUSSEAU Maine University | HTML 5 Java Script |
| QuTiP - Quantum Toolbox in Python | J. R. Johansson, P. D. Nation, and F. Nori | Python |
| Physics Educational Software (weber.edu) | Daniel V. Schroeder | HTML 5 Java Script |
| Teaching quantum physics by the sum over paths approach and GeoGebra simulations | [13] | GeoGebra |
| O.S.P quantum Physics Simulations Search Results | Wolfgang Christian, and his team About OSP (compadre.org) | Java, Java Script |
| FuncXY, TriPlot 3D Graphing, Graphing calculator | [12] | Android |
| Excited States and Photons:http://concord. org/stem-resources/ | Concord Consortium team Staff – Concord onsortium | Java |
| Visual Quantum Mechanics VQM Tutorials (ksu.edu) | Team of Kansas State University Physics Education Research https:// perg.phys.ksu.edu/info | Java, Visual Basic |
| Relequant project Quantum Physics (viten.no) | Anniken Dybwad Arnt Inge Vistnes Siri Fløgstad Svensson Susanne Viefers University of Oslo) | HTML et JavaScript |
| Falstad Quantum Math, Physics, and Engineering Applets | Paul Fastled | Java, JavaScript |

### 3.2.2. Effectiveness of Integrated Simulations in Learning Strategies for Quantum Concepts

Have these simulation tools been integrated into the teaching/learning of quantum mechanics? Furthermore, have they developed the students' understanding of quantum concepts? Moreover, have they changed the students' attitude towards learning quantum mechanics?
In this context, several studies have evaluated the effectiveness of these tools by the results of the different tests performed.

Indeed, in the study of Singh [6], the authors have proven the effectiveness of QuILTs simulations to improve the understanding of the concept of the temporal development of the wave function from 53% to 85%, and the improvement of the understanding uncertainty principle from 42% to 83%. Table 3 shows the investigation results after using these simulation and visualization tools.

Table 3. Studies that have shown the effectiveness of simulation in learning quantum concepts

| Authors | Projects of simulation | Pre-test Or did not used simulations | Post-test Or used simulations |
|---|---|---|---|
| [5] | Quvis simulation | Did not used simulations | Used simulations |
| | | 18% | 59% |
| | | 18% | 64% |
| [9] | QuILTs | Did not used simulations | Used simulations |
| | | 40% | 100% |
| | | 3% | 77% |
| | | 35% | 96% |
| [7] | Phet | 36% | 92% |
| [14] | Physlets | Pre-test | Post-test |
| | | 11% | 66,25% |
| [15] | Phet simulation | Did not used Simulations gain | used simulations gain |
| | | 0.89 | 1.20 |
| [6] | Spins Program | Pre-test | Post-test |
| | | 52% | 92% |
| | | 37% | 84% |
| [16] | QShakeIt | Pre-test | Post-test |
| | | Average gain up to 20% | |
| [17] | Visualization of wave's function | 88% of success | |

### 3.2.3. Virtual Lab

Experimentation plays an essential role in physics learning; it develops scientific process skills. Nevertheless, the real laboratories have some limitations, are challenging to integrate into the classroom during the course, need a long time, sometimes their cost is high, lack of laboratory equipment, and the concern of teachers to complete the program. Therefore, with the development of ICTs, the virtual laboratories based on computer simulation constitutes an alternative tool for laboratory experimentation [15].

Indeed, virtual labs are easy to operate tools and require less time [29], they are indispensable in distance learning. Virtual labs can also play an important role in understanding abstract concepts. As an example, the virtual experiment of the photoelectric effect in the study of Ranjan [15]; this virtual lab allows learners to easily experiment with different parameters to building a mental model of photons.

The exploitation of the interferences obtained by the Mach Zender virtual interferometer allows easy integration during the course by supporting the teacher's explanation to show the photons' corpuscular and wave aspects [13]. Table 4 shows the different projects of virtual labs integrated into learning quantum concepts.

Table 4. Virtual labs integrated into learning quantum concepts

| Project | Authors | Virtual experiment |
|---|---|---|
| Teaching quantum mechanics on an introductory level | [1] | The Mach–Zehnder interferometer |
| Application IMZ Index of /~fernanda/IMZ (ufrgs.br) | Fernanda Ostermann, Sandra D. Prairie et Trieste de SF Ricci, Physics institute, Federal University of Rio Grande do Sul | The Mach–Zehnder interferometer |
| Phet http://phet.colorado.edu | K. Perkins, C. Wieman and their Phet team https://phet.colorado.edu/en/about/team | photoelectric effect, Davisson-Germer Experiment Stern Gerlach Experiment |
| Visual quantum Visualization VQM Tutorials (ksu.edu) | Team of Kansas State University Physics Education Research https://perg.phys.ksu.edu/in | Spectroscopy experiments, Franck-Hertz experiment, Photoelectric effect |

### 3.2.4. Programming

Other researchers have used instead of interactive simulations programming languages such as C++, Java, MATLAB, Python, Mathematica. Researchers resort to the use of programming, for example, when solving the Schrodinger equation. Indeed, solving the equation by hand for the one-dimensional case in a simple potential is a task that is not difficult. However, with the complication of nonlinear potential and systems, learners face complicated mathematical difficulties [18], especially when learners make various changes to study the impact of these changes [18].

Hence, the need to develop programs to solve Schrodinger's equation quickly makes learners focus on the results of the solution instead of getting lost in the difficulties of solving it. Programming is a tool that allows learners to visualize the results of solving the Schrodinger equation [18], the development of a quantum state, the interaction of a wave packet with a potential barrier etc. Table 5 shows the different programming projects and concepts targeted for understanding.

Table 5. Programming projects in learning quantum concepts

| Projects | Authors | Language of development |
|---|---|---|
| Physics with Maple | [19] | Maple |
| the interactive program of quantum mechanics | [20] | Java |
| The Schrodinger.py program http://pubs.acs.org/doi/suppl/10.1021/acs.jchemed.7b00003/suppl_file/ed7b00003_si_001.zip | [18] | Python |
| Quantum Mechanics Using Mathcad | [21] | Mathcad 3.0 |
| Visualization of Wave Functions Using Mathematica | [17] | Mathematica |
| DoQO | [22] | C++ (require Fortran) |
| WavePacket | [23] | MATLAB |

### 3.2.5. Computer Games

According to the socio-constructivist theory of learning, games have a significant role in learning; the learner in the game finds passion, desire, then he engages and mobilizes his knowledge, abilities, and attitude skills, and during this process of play, learning becomes active.

It should be noted here that we are talking about two things, the use of games in learning quantum mechanics and the integration of game processes called gamification in learning.; especially in recent years, several types of research have shown the opportunities offered by gamification, which based on the attraction and reward throughout the learning journey which hooks the player (learner) to continue until completion.

In the case of learning quantum concepts that are too abstract and counterintuitive to engage students in the active learning of quantum mechanics, researchers propose the integration of games and gamification in teaching of quantum mechanics, in this context, researcher Gordon's [24] propose an exciting game called "Schrödinger cats and hounds" to understand some counterintuitive concepts of quantum mechanics, such as superposition, measurement process, it's available in http://gorengordon.com/qgames, a post-test results showed an improvement in learning the quantum concepts studied in this study. Table 6 shows some of the game's projects used in different projects for learning quantum concepts.

Table 6. Computers game projects in learning quantum concepts

| Authors | Project |
|---|---|
| [25] | quantum minesweeper http://gorengordon.com/qgames/ Quantum Minesweeper/qMinesweeper.html |
| [26] | Particle in a Box |
| [8] | Student Researcher: Quantum Moves 2, Lab Manager, Quantum Pattern Matching Game Science At Home \| Games |
| [16] | QShakeIt and QShake Up & Down |

### 3.2.6. Cartoons

The presentation of quantum mechanics in its mathematical formalism presents a demotivating factor, so in this context, to bring the quantum ideas and concepts closer to the learners, the group of Lautesse suggested the use of cartoon books entitled the mystery of quantum world [4] in a didactic use. Indeed, cartoons are pedagogical supports that allow illustrating some quantum ideas and phenomena that are inaccessible at the subatomic scale and allow to vulgarize the quantum ideas.

Another series of cartoons in video, elaborated by the physicist Fred Alan Wolf, is presented by a cartoon character called Dr. Quantum; in this cartoon series, several concepts are explained, such as quantum entanglement and the double-slit experiment.

### 3.2.7. E-Learning

#### 3.2.7.1. Platform for Teaching Quantum Mechanics

The development of platforms becomes a necessity with the development of ICTs; and the use of platforms has become an obligation during periods of confinement, such as an example of the pandemic covid 19. Therefore, several universities have developed platforms for students to access and interact with several digital resources and interact with the teacher. In this context, we present two exciting platforms used for teaching/learning quantum mechanics, the project REL equant [11] and the Physlet project [27].

The Physlet Quantum Physics 3E platform is hosted in the site Physlet Quantum Physics (www.compadre.org ), its curriculum available on the web, contains 15 interactive chapters containing simulations that illustrate some phenomena and quantum concepts; some simulations allow interactivity to understand well the quantum concepts, teaching via Physlet based on the JITT technique (Just-in-time teaching) [14], the activities in the form of online courses linked with simulations demonstrations, animations, exercises and problems to do which are web-based tools to engage learners in active learning based on visualization and learner-teacher feedback, the simulation's physlet are accessible, flexible and interactive, they are developed in JavaScript/Html 5 and intended for introductory and intermediate level in quantum mechanics [27].

The ReleQuant platform is a web-based teaching, organized as a curriculum for teaching quantum mechanics to upper secondary students. The ReleQuant project is hosted on the Quantum Physics website (www.viten.no ), and consists of 5 modules; the philosophy of the ReleQuant project is based on the theory of socioconstructivist learning which suggests the use of language in understanding, so in this project there is a presentation to the learners of videos bearing the explanations of physicists followed by discussion with peers while asking them to write down what engages them in learning, simulations allowing the illustration of phenomena and experiments, tasks to do, exercises. The use of discussion and conversation in the Relequant project allowed to engage 64% of the students in productive discussions about the nature of light and 78% of the students in the discussion of the Schrodinger cat experiment [28].

#### 3.2.7.2. The MOOCs

Today, the MOOCs constitute effective teaching platforms open to any public, especially with the development of ICTs, the development of distance learning technologies, the development of computer technologies, and the development of the quality of networks and web. Indeed, MOOCs present an important opportunity to engage learners in learning as they allow the integration of a rich environment of technological resources of different multimedia, texts, interactive exercises, image, videos, simulations, tutorials, the following Table 7 presents some MOOCs designed for the teaching/learning of quantum mechanics.

Table 7. The important MOOCs used in the teaching of quantum mechanics

| MOOC name | Authors |
|---|---|
| Quantum Mechanics for Everyone<br>Quantum Mechanics for Everyone \| edX | James Freericks<br>Professor at Georgetown University |
| Foundations of Quantum Mechanics \| Coursera | Wounjhang Park University of Colorado Boulder |
| Understanding Modern Physics II: Quantum Mechanics and Atoms \| Coursera | Yi Wang<br>The Hong Kong University |
| Quantum mechanics \| Coursera | John W. Daily |
| Quantum mechanics \| Coursera | Jean Dalibard , Philippe Grangier, Mathieu de Naurois Manuel Joffre |
| Quantum Physics I | Barton Zwiebach |
| Mastering Quantum Mechanics Part 1: Wave Mechanics \| My MOOC | Barton Zwiebach and Saif. Rayyan |
| Quantum Mechanics I > Mod-01 Lec-01 Quantum Mechanics -- An Introduction\| Class Central Classroom | S. Lakhsmi Bala<br>Indian institute of technology Madras |

### 3.3. Disadvantages of Using ICTs in Teaching / Learning

Despite the important advantages that the new ICts allow in enhancing learning of quantum mechanics, there are limitations, obstacles, and disadvantages. Indeed, despite simulation is an emerging technology not only in the field of education, but also in the fields of medicine, engineering, building design [30], ..., they do not represent reality in its totality and complexity; they are programmed from mathematical models; on the other hand, virtual experiences do not develop some skills that real experiences do.

The integration of ICTs is confronted with several institutional and didactic limitations; at the level of teachers, there is a lack of technological skills, which limits the integration of ICTs in the teaching process, on the other hand, the negative attitudes of some teachers limit the use of ICTs in teaching. At the level of the learner, several limitations arise; indeed, the absence of a face-to-face teacher reduces communication and limits socialization, which are two essential factors in the learning process according to socioconstructivist; also, the explanation and interpretation may be less effective. E-learning creates an environment of isolation and remoteness of learners given the lack of interactivity, this poses the problem of lack of motivation and lack of independence, which makes learners demotivated and their successes decline.

However, with the continuous and rapid technological advances, these problems are becoming less frequent. Nowadays, learners can interact and cooperate effectively with each other using ICTs. It is necessary to train learners on self-study, self-assessment, and self-organization; it is necessary to develop skills such as information time management and technological skills. At the teacher level, technological skills need to be developed, and teachers need to be trained on new perspectives of planning and classroom management that consider the integration of ICTs.

## 4. CONCLUSION

Given the complex nature of the discipline of quantum mechanics, the difficult level of abstraction, not intuitive quantum concepts, complicated mathematical formalism, and the persistence of classical paradigms; to overcome these difficulties, several tools have been developed, such as computer simulations, programming, cartoons, and games. Studies that have integrated these new ICTs in the classroom have proven that they have increased students' comprehension.

However, a profound reflection on the use of new information and communication technologies must be done to overcome the different limitations of ICT in teaching/learning quantum mechanics, at the level of learners, teachers, computer transposition, and at the institutional level.

On the other hand, teaching practices must be changed for active, motivating, and interactive methods to introduce and discuss the interpretation of quantum concepts. The revision of programs and content is a primary necessity. Moreover, it is necessary to introduce quantum mechanics in the high school curriculum early.

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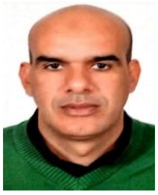

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