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Experimental and Didactical Strategy to Improve Understanding of the Fundamental Concepts in Quantum Physics.

Abstract: - Quantum physics is an essential theory serving to explore nature at its smallest scales. Interaction between elemental particles in matter is leading toward new potential alternatives for producing decarbonized clean energies. Despite its importance, students find difficulties in understanding quantum mechanics due to a wrong categorization of the fundamental concepts. Studying quantum physics needs a new flexible ontology in which the quantum entity can have particle or wave properties depending on the context. We developed a workshop in quantum devices to put concepts into the correct conceptual categorization. With the aim of strengthening interinstitutional exchange, we realized the workshop with a population conformed by environmental engineering students of the Corporación Universitaria Uniagraria. Meeting took place in the Institución Universitaria Politécnico Grancolombiano facilities. Laser, LED (Light Emitting Diode), and photocell were the devices used to introduce the most fundamental concepts of quantum physics. The theoretical component of the workshop was divided into two main elements, the first, radiation-matter interaction, and the second, electrical transport mechanisms in materials. Pedagogical instruments employed were diagnostic proof, evaluative proof, and satisfaction inquiry. Despite the success achieved in the general realization of the workshop, students suggested some aspects for considering in future versions.

Keywords: Electron, LED Diode, Photocell, Photon.

I. INTRODUCTION

Quantum physics is seen as one of the cornerstones of modern physics together with Einstein's theory of general relativity. It is an essential theory to understand nature at its smallest scales. Its development during the twentieth century has been crucial for the expansion of modern technologies such as semiconductors, lasers, quantum computing, encryption, and teleportation [1], [2]. For conceiving a considerable fraction of these technologies, quantum optics understanding is indispensable; this subject considers optical phenomena that can only be explained by treating light as a stream of photons rather than as electromagnetic waves [3].

Decarbonized clean energy such as solar energy, wind energy, and geothermal energy has become the solution to global warming, energy crisis, and environmental pollution [4], [5]. For example, quantum dots have attracted extensive attention for their potential electrochemical energy storage due to their adjustable size, non-toxicity, low cost, and adjustable photoluminescence [5], [6]. Graphene quantum dots (GQDs) have been studied as an advanced material for electrodes in electrochemical energy storage (EES) systems such as batteries and supercapacitors [7]. Another interesting alternative is represented by photovoltaic technologies based on the principle of electron-hole creation into semiconductor materials [8].

The origin of all sustainable energy available on Earth is the Sun. In a physics book about energy, it is logical to start by understanding how the Sun generates this sustainable energy. Immediately, it turns out that quantum physics can be extended to other necessary aspects, at solid matter, for studying semiconductor devices like solar cells, lasers, and LED diodes [9]. At this point, a substantial question becomes how far can emerging quantum technologies arrive at providing advantages related to anthropogenic climate change in areas such as mitigation and adaptation [10]. Last question finds a close relation with the Sustainable Development Goals (SDG), or the seventh about affordable and clean energy production.

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Quantization explains the nature of light, energy, and angular momentum in the atomic world. Since it is the underlying premise of quantum theory, it cannot be considered like an isolated concept taught in a modern physics or quantum physics course [11]. Despite the remark, these courses are often described as challenging because they are considered like abstract [2], [11], [12]; the main reason for that is an incorrect conceptual categorization conducing to difficulties in constructing a knowledge structure led by a few core ideas [13], [14]. Due to the crucial role of quantum mechanics for the sustainable development, the present work proposes a theoretical-practical strategy pursuing an improvement in understanding level of the most fundamental topics in modern physics.

We will introduce the development of the didactical strategy as follows. Section state of the art will treat the most fundamental concepts about modern physics and the challenge concerning to the teaching of quantum mechanics. Section method will explain the didactical strategy under four criteria; performed strategy, population, instruments, and data collection and analysis procedure. Results of this survey will be introduced under the topics mentioned below; first, the didactical strategy used for constructing the theoretical fundaments; second, the experimental work for verifying the concepts at the first topic; and third, the proofs and inquires for evaluating the performance of the students and the effectiveness of the didactical strategy. We will finish by giving some general conclusions.

II. STATE OF THE ART

A. Fundamental regard about modern physics

Regardless of the source of radiation, electromagnetic waves of frequency ω can be considered like a stream of particles named photons. A photon is a bundle of energy being initially localized in a small volume of space and remains localized as it moves away from the source with velocity c. Particle parameters (energy E and momentum $\vec{p}$ of a photon) and wave parameters are linked by the fundamental relations,

$$E=\hbar\omega \quad (1)$$

$$\vec{p}=\hbar\vec{k} \quad (2)$$

During each elementary process, energy and total momentum must be conserved [15] – [17].

A given atom emits or absorbs only photons having well-determined frequencies. This fact can be interpreted very easily if one accepts that the energy of the atom is quantized, that is, it can take on only certain discrete values E_n $(n=1,2,\ldots)$. Emission or absorption of a photon is then accompanied by a change in the energy of the atom from one permitted value E_i to another E_f. Of course, frequency ω_{if} of the photon emitted in a transition is related to the change in the energy of the atom. Frequency of the emitted radiation is found from the energy-conservation expression,

$$E_i-E_f=\hbar\omega_{if} \quad (3)$$

E_i is the energy of the initial state, E_f is the energy of the final state, and $E_i>E_f$. The energy of an incident photon can be absorbed by the atom, but only if the photon has an energy that exactly matches the difference in energy between an allowed state of the atom and an upper-energy state. Upon absorption, the photon disappears, and the atom makes a transition to the higher-energy state. Bohr postulates about atomic model implies qualitatively the existence of a characteristic discrete emission line spectrum and a corresponding absorption line spectrum [15] – [17]. Fig. 1 explains graphically the fundamental processes related to the electron-photon interaction for atoms into a cavity.

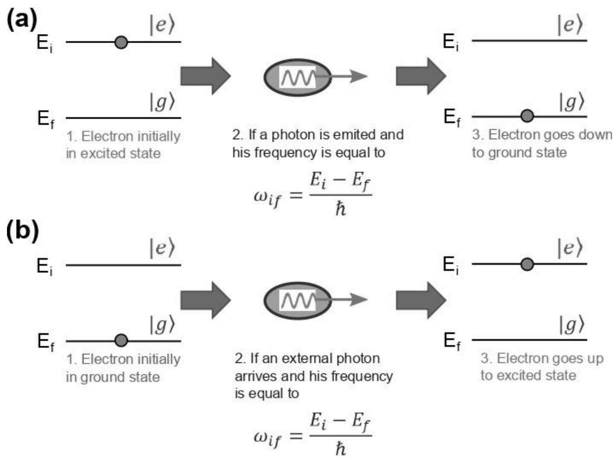

Fig. 1. Fundamental processes related to electron-photon interaction for atoms into a cavity, (a) absorption and (b) emission of photons.

It is impossible to explain all physical phenomena observed if only one of the two aspects of light, wave, or particle, is considered. These two aspects seem to be mutually exclusive. To overcome this difficulty, however, it becomes indispensable to reconsider the concepts in a critical way. Wave-particle duality can be summarized as follows [15],

- Particle and wave aspects of light are inseparable. Light behaves simultaneously like a wave and like a flux of particles, the wave enabling us to calculate the probability of manifestation of a particle.

- Predictions about the behavior of a photon can only be probabilistic.

- Information about a photon at time t is given by the wave $\vec{E}(\vec{r}, t)$ which is a solution of the Maxwell's equations. $\vec{E}(\vec{r}, t)$ is interpreted as the probability amplitude of a photon appearing, at the time t, at the point $\vec{r}$. This means that the corresponding probability is proportional to $|\vec{E}(\vec{r}, t)|^2$.

In 1923, Louis de Broglie puts forth the following hypothesis: material particles, just like photons, can have a wavelike aspect. Just as a photon has a light wave associated with it that governs its motion, so a material particle has an associated matter wave that governs its motion. Since the universe is composed entirely of matter and radiation, the suggestion of de Broglie is a statement about a grand symmetry of nature. Indeed, one can associate with a material particle of energy E and momentum $\vec{p}$ a wave whose angular frequency $\omega = 2\pi\nu$ (ν is the frequency) and wave vector $\vec{k}$ are given by the same relations as for photons, that is, by (1) and (2). According to the original de Broglie hypothesis, corresponding wavelength λ is $\lambda = \frac{2\pi}{\|\vec{k}\|} = \frac{h}{\|\vec{p}\|}$ ($h = 6,626 \cdot 10^{-34}\ J \cdot s$ is the Planck constant) [15] – [17].

If we wish quantically describe the mechanisms of electrical transport in solids, we need to express energy of the electrons like a function of the wavevector $\vec{k}$. This function is usually called energy band $\varepsilon(\vec{k})$. Tables 1 and 2 show the most relevant features of four main mechanisms of electrical transport considered for several technological inventions.

Table 1. Relevant features about two mechanisms of electrical transport, metallic, and semiconductor.

Electrical transport features	**References**
METALLIC	
• Electrical conductivity is due to the outer-shell electrons being free to move through the	[17] – [22]

metal but trapped within a three-dimensional box formed by the metal surfaces. • Conduction electrons are described only by the conduction band $\varepsilon(\vec{k})$ written as $\varepsilon(\vec{k}) = \frac{\lVert\vec{p}\rVert^2}{2m} = \frac{\hbar^2\lVert\vec{k}\rVert^2}{2m}$. • The highest energy value taken by an electron in the conduction band is Fermi energy ε_F; it depends on the temperature and the crystalline structure of the metal. • Only electrons whose energy value is near to ε_F can contribute to the electrical conductivity of the metal. • All thermic, electric, and magnetic phenomena are explained through the free electron model employing Fermi-Dirac distribution function. • Examples: Au, Cu, Ag, Zn, Ti, Na, K, Fe.	
SEMICONDUCTOR • The model is more sophisticated than the case of the metal electrons. Now, the contribution of the periodic atoms forming the crystal is incorporated. • Wavevector $\vec{k}$ of the electron runs through all wave vectors in a single primitive cell of the reciprocal lattice in consistency with the Born-von Karman periodic boundary condition. • There are two bands, valence band, VB, and conduction band, CB. Close to $\vec{k}=0$ (First Brillouin zone), their functions are respectively $\varepsilon_{VB}(\vec{k}) = -\frac{\hbar^2\lVert\vec{k}\rVert^2}{2m_V}$ and $\varepsilon_{CB}(\vec{k}) = \varepsilon_g + \frac{\hbar^2\lVert\vec{k}\rVert^2}{2m_C}$. • For $\vec{k}=0$, the difference $\varepsilon_{CB}(0) - \varepsilon_{VB}(0)$ is equal to the band gap energy ε_g. • An electron transition from VB to CB is carried out by the absorption of a photon whose energy is higher than the band gap energy ε_g. Instead, a photon is produced if an electron initially in CB falls to VB. • Examples: InGaN, GaN, Si, AlN, GaAs, AlGaInP, TiO_2, ZnO.	[17], [19], [20], [23].

Table 2. Relevant features about two mechanisms of electrical transport, superconductor, and graphene.

Electrical transport features	**References**
SUPERCONDUCTOR • For temperature values $T<T_C$ (T_C is the critical temperature), surface currents induced on the superconductor surface produce a magnetic field exactly canceling with externally applied field inside the superconductor, namely, an applied magnetic field is expelled by the sample and the field becomes zero in its interior (Meissner effect). • All thermic, electric, and magnetic phenomena are explained through the BCS theory. This theory is based on Cooper pairs consisting in two electrons interacting via distortions in the array of lattice ions. • Function $\varepsilon(\vec{k})$ is like in the metallic case, but electrons forming Cooper pairs have their energy close to Fermi Energy ε_F. • Quantum state of a Cooper pair is denoted like $(\vec{k}\uparrow, -\vec{k}\downarrow)$, arrows refer to the electronic spin state (up and down). • Probability of the pair $(\vec{k}\uparrow, -\vec{k}\downarrow)$ being occupied is $\lvert v(\vec{k})\rvert^2$, and the probability of being unoccupied is $\lvert u(\vec{k})\rvert^2 = 1 - \lvert v(\vec{k})\rvert^2$. These probabilities can be expressed in terms of $\varepsilon(\vec{k})$.	[17], [20], [24], [25].

- Examples: Hg, Nb, Te, V, Nb_3Al, $Yb_{0.9}Ca_{0.1}Ba_{1.8}Sr_{0.2}Cu_4O_8$.

GRAPHENE

- Graphene is a two-dimensional crystal with a hexagonal structure. [26] – [28].
- Carbon atoms form an array constructed as a superposition of two triangular lattices.
- Energy band functions $\varepsilon(\vec{k})$ can be expressed in the close form $\varepsilon\left(k_x, k_y\right) = \pm\gamma_0\sqrt{1 + 4\cos\left(\frac{\sqrt{3}k_x a}{2}\right)\cos\left(\frac{k_y a}{2}\right) + 4\cos^2\left(\frac{k_y a}{2}\right)}$. Term γ_0 is the transfer integral between the nearest neighbors, a is the hexagon side length at the atomic array, and $\vec{k} = k_x\hat{u}_x + k_y\hat{u}_y$ is the two-dimensional electronic wave vector.
- Interactions between electrons, photons and acoustic phonons can be found in the atomic structure.

In closing, three quantum devices, candidates for producing sources of clean energies and whose structures are illustrated in fig. 2-4, will be shortly described,

- Laser: quantum device that produces extremely bright beams of coherent light (fig. 2). His behavior is based on simultaneous processes concerning the emission and absorption of photons from the atoms at the gain medium of device. In the spontaneous emission process, the atom is initially in an upper state of energy ε_2 and decays to a lower state of energy ε_1 by the emission of a photon of frequency $\omega = \frac{\varepsilon_2 - \varepsilon_1}{\hbar}$. For achieving processes of stimulated absorption and emission, it is essential before to produce a population inversion by carrying many atoms to the excited state; this phenomenon is called population inversion and takes place by pumping energy into the gain medium [3], [16], [17].

- Light-emitting diodes (LED): relative to the depletion region of the *p-n* junction, an electron excited electrically into the conduction band can easily recombine with a hole, especially if the electron passes into a *p* region. As this recombination takes place, a photon of energy ε_g is emitted (fig. 3). With a proper design of the semiconductor and the associated plastic envelope of mirrors, the light from many of these transitions serves as the source of a LED or a semiconductor laser [17], [29].

- Solar cell: the solar cell is a solid-state device which converts sunlight, as a stream of photons, into electrical power. There are two silicon layers forming a typical solar cell, one of them has been doped with boron (piece p-type) and the other one with phosphorus (piece n-type). Due to built-in potential of the p-n junction (fig. 4), electrons migrate to the n-type region and generate electric power like an electrochemical battery [29].

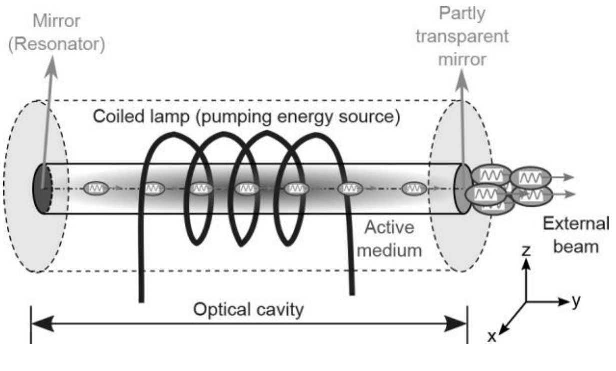

Fig. 2. Internal structure of a laser. Graphic shows briefly the production of an external coherent light beam.

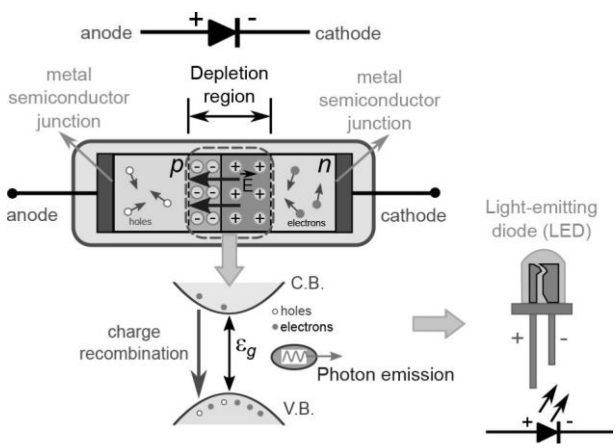

Fig. 3. Internal structure of a light-emitting diode (LED). Due to the charges recombined in the depletion region, LED produces light whose frequency is proportional to the gap energy (ε_g) related to semiconductor junctions.

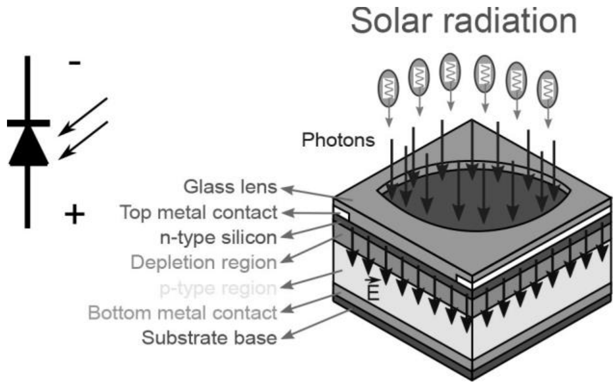

Fig. 4. Internal structure of a solar cell; p-n junction allows electrons to migrate to the n-type region and generate electric power like an electrochemical battery.

B. Challenges about quantum mechanics teaching

Learning physics requires drawing meaningful inferences and applying the few fundamental physical principles, available in compact mathematical forms, to diverse situations. To develop a functional understanding, students must focus on the physics concepts while solving problems and be able to pass at once between the mathematics and the physics, regardless of whether they convert a physical situation to a mathematical representation or contemplate the physical significance of the results during problem solving [30].

Some investigations suggest a large diversity for the student performance in the quantum mechanics courses indifferently of the university, textbook, or instructor, and many students in these courses have not acquired a functional understanding of the fundamental concepts [30] – [32]. These surveys are realized in several universities at same time and have gotten to test, from a theoretical perspective, attractive strategies allowing to improve notoriously the comprehension about quantum mechanics issues [30]. A general goal in this kind of works is the fact of helping students learn to “think like a physicist,” skill quite useful in the frame of many physicist courses from the introductory to the advanced level. For becoming an expert in physics, the development of problem-solving, reasoning, and metacognitive skills must go hand in hand with learning content and building a robust knowledge structure [30].

In recent years, quantum mechanics has appeared in many secondary school curricula for some European nations [1], [2]. In that context, teaching must be carried out at a more conceptual level, but the challenge consists in making understandable counterintuitive concepts, like wave-particle duality, without introducing mathematical formalism. These curricula often do not include the mathematical tools for a formal introduction [1], [2]. Some researchers, in direct contact with students, have been focused on trying the difficulties around understanding of the wave-particle duality, and another have focused on two-level quantum states. Another way of introducing quantum mechanics, which has been investigated less frequently, is to introduce the infinite one-dimensional potential well and the tunnel effect [1], [2].

C. Importance of developing a didactical strategy

A fundamental goal of the science education is for the students to develop a deep understanding of disciplinary core ideas such that they can apply the knowledge to solve complex problems in novel situations [14]. Limited to remembering context-specific solutions with little generalization, students in turn tend to use pattern matching when solving problems and demonstrate little conceptual understanding [14]. An ideal learning process is one where knowledge structures are integrated and hierarchically arranged around a few core principles with well-established links connecting a wide range of conceptual components related to the content domain [14]. These connections form a comprehensive network that links concrete contextual features with core conceptual ideas so that knowledge cannot be reduced to simple set of isolated facts or propositions [14].

According to the conceptual change theory developed by Chi [13], there are three ontological categories: entities, processes, and mental states. From this perspective, misconceptions occur when new concepts are miscategorised, and students need to move a concept from one ontological category to another [13]. Since particles belong to the ontological category entities and waves to the category processes, a new ontological category is essential for learning quantum mechanics. Students need to embrace a new flexible ontology in which the quantum entity can have particle or wave properties depending on the context; this conceptual change is achieved if the new theory is understandable, logical, and useful [1].

Exploring the reasons for the perceived abstract nature of quantum physics allows a better understanding of the origin of the students' conceptual difficulties [2]. An expected tangible result must be overcoming of the student's conceptual difficulties through the design of a general methodology conducing to the simultaneous interaction between teachers and students for supporting conceptual development of the quantum physics. For this reason, we have proved a practical strategy for introducing engineering students in the quantum mechanics concepts. In our teaching approach, experimental work is realized by exploiting some quantum devices like LED diodes, photocells, and lasers. Through their operation, students can understand and put into a new ontological category the most fundamental concepts in quantum mechanics.

III. METHOD

A. Performed strategy.

To explain quantization and identify students' mental models about quantization, we chose a context related to alternatives for developing sustainable energies. We structured the workshop into four parts described as follows,

- Diagnostic exam application for evaluating initial understanding and knowledge of the students about modern physics topics.

- Realization of a seminar concerning the most fundamental theoretical concepts in modern physics.

- Experimental approach. The students were familiarized with relevant quantum devices (laser, LED diode, and photocell) through two experimental practices. In the first, a LED diode lit thanks to the voltage difference delivered by a photocell. The second practice showed the change in magnitude of the electrical conductivity for different electrical transport mechanisms in materials.

- Like the final stage in the workshop, we applied an evaluative exam and a satisfaction inquiry.

B. Population

With the aim of strengthening interinstitutional exchange, we realized the workshop described in this work with a population conformed by environmental engineering students of the Corporación Universitaria Uniagraria. Meeting took place in the Institución Universitaria Politécnico Grancolombiano facilities.

C. Instruments

We employed three instruments. The first was a diagnostic exam, and the second, after theoretical and practical activities, consisted of an evaluative exam. Like third instrumental resource, we applied a satisfaction inquiry. Collected information by these instruments was correlated for assessing the effectiveness of the methodological strategy and establishing improvement programs.

D. Data collection and analysis procedure

We collected data through a Conceptual Understanding Test (CUT) conformed by multiple choice questions [33] – [35]. Diagnostic and evaluative exams were proposed like CUT proofs, and both were presented by 15 students. The CUT was conceived from the following search questions,

- What are the conceptual comprehension levels in the students referring to the quantization principle applied to the electromagnetic radiation and matter?

- How are the mental models produced by the students about the most fundamental phenomena tried in quantum mechanics?

With the purpose of quantifying the progress in the conceptual appropriation of modern physics topics, we individually assigned scores between 100 (3), 67 (2), 33 (1) and 0 points (0 correct answers) to each general element considered in both diagnostic and evaluative proofs (table 3). Tables 4-7 show the applied questions (and their correct answers) belonging to the diagnostic and evaluative test. To measure students' perception about workshop developed, we employed Microsoft Forms tool at the design and application of a satisfaction inquiry (table 8).

Table 3. Evaluation criteria for each general element constituting the diagnostic and evaluative tests.

General element	Evaluation criteria
First element: Radiation-matter interaction.	Photon, electromagnetic waves, discrete energy levels, Bohr atomic model for hydrogen atom, two level systems, photon absorption and emission, coherent light, laser.
Second element: Electrical transport mechanisms in materials.	De Broglie hypothesis, energy band function $\varepsilon_n(\vec{k})$, metals, semiconductors, superconductors, graphene, LED diodes, photocells.

Table 4. Questions detail about the first element, radiation-matter interaction, at the diagnostic proof.

Subject	Question	Correct answer
Photon.	For electromagnetic waves, associated color for a light beam depends on,	The radiation frequency.

Photon, discrete energy levels.	What is the factor allowing conversion for an energy value from Joules (J) to electronvolts (eV)?	$1\ eV = 1,602.10^{-19}\ J.$
Photon, discrete energy levels, Bohr atomic model for hydrogen atom, two level systems, photon absorption and emission.	The best sentence for detailing transition of an electron, at the hydrogen atom, from the third energy level, $n=3$, to second energy level, $n=2$, is,	Atom emits a photon with energy equal to $1,9\ eV$. Photon wavelength is $652\ nm$ (red).

Table 5. Questions detail about the second element, electrical transport mechanisms in materials, at the diagnostic proof.

Subject	**Question**	**Correct answer**
De Broglie hypothesis.	An alternative form for explaining de Broglie hypothesis would mention that,	For a particle, there is a direct proportional relation between its wavevector ($\vec{k}$) and its linear momenta ($\vec{p}$). Universal proportionality constant is Planck reduced constant $\hbar$.
Energy band function $\varepsilon_n(\vec{k})$, metals.	For the metallic conducting electrons, what is the affirmation NOT related with the Femi energy (ε_F)?	For a conducting electron inside metal, energy only can be equal to the Fermi energy (ε_F).
Energy band function $\varepsilon_n(\vec{k})$, semiconductors.	Smallest difference between an energy value at the conduction band (BC) and other at the valence band (VC) is called,	Optical gap energy (ε_g).

Table 6. Questions detail about the first element, radiation-matter interaction, at the evaluative proof.

Subject	**Question**	**Correct answer**
Photon, discrete energy levels, Bohr atomic model for hydrogen atom, two level systems, photon absorption and emission.	For an atomic electron, what condition is required for allowing an electronic transition from the initial level E_i to final level E_f? The final energy value is higher than the initial energy value.	A photon whose energy is equal to the difference between electronic energy levels final and initial of the atom (that is, mathematically, $\Delta E = E_f - E_i$) must be equal to the photon energy absorbed by the atom.
Photon, two level systems, photon absorption and emission, coherent light, laser.	Laser is a quantum device that produces coherent electromagnetic radiation. Optical coherence of the light is a property referring to some features, what are these features?	Electric field $\vec{E}(\vec{r},t)$, describing coherent light, keeps its phase function into an infinite interval for the space and time. For a light diffraction experiment, coherence is related with the visibility, during an infinite time, of the luminous and dark fringes patterns.

Photon, electromagnetic waves.	X-rays are electromagnetic radiation used at radiographies ($\lambda = 1,5\ \mathring{A}$). Infrared electromagnetic radiation is used at nocturn vision devices ($\lambda = 2500\ nm$). According to this information, one of these sentences is FALSE,	An X-rays photon has the same energy as an infrared photon.

Table 7. Questions detail about the second element, electrical transport mechanisms in materials, at evaluative proof.

Subject	Question	Correct answer
De Broglie hypothesis, energy band function $\varepsilon_n(\vec{k})$, metals, semiconductors, superconductors, graphene.	What is the difference between a bound electron into an atom and a bound electron into a solid crystal?	While, into an atom, electron takes discrete energy values named energy levels (E_n), into a solid crystal, electron energy is described through $\varepsilon_n(\vec{k})$ functions called energy bands.
De Broglie hypothesis, energy band function $\varepsilon_n(\vec{k})$, semiconductors, photocells.	A solar photocell must be built by using a specific material kind. What is this material? Why must it be used?	Semiconductor materials. These materials transform solar radiation energy into a potential difference.
De Broglie hypothesis, energy band function $\varepsilon_n(\vec{k})$, superconductors.	In case of superconductor materials, the most complete way for defining a Cooper pair consists in mentioning that,	It is formed by an electron pair. Both have their wavevector with the same magnitude but oriented in opposed senses. For both particles, signs of spin quantum number are contraries. In both electrons, energy is near to Fermi energy ε_F.

Table 8. Details of questions proposed in the satisfaction inquiry. Students assigned some grades into scale.

Question	Grade scale
IQ1: How familiarized were you with fundamental concepts of modern physics before taking Quantum Devices Workshop?	0 (not familiarized), 1, 2, 3, 4, and 5 (completely familiarized).
IQ2: How much comprehension did you achieve about modern physics concepts after Quantum Devices Workshop?	0 (I achieved not understanding), 1, 2, 3, 4, and 5 (I get full understanding about fundamental concepts).
IQ3: What is your satisfaction level relative to the development of Quantum Devices Workshop?	0 (not satisfied), 1, 2, 3, 4, 5 (fully satisfied).
IQ4: Did workshop experimental component serve for finding a relation between Quantum Devices (photocell, LED diodes, and laser) and the alternative searching to produce clean energies?	Students chose YES or NOT.
IQ5: What would your tip be for considering future versions of Quantum Devices Workshop?	Students wrote their answers openly.

IV. RESULTS AND DISCUSSION

A. Theoretical component

We developed theoretical aspects concerning the workshop through a conventional expert exhibition. Students had access to the lectures about two main elements described in table 3. We elaborated infographics with the aim of putting the most crucial details about theoretical fundaments. Infographics consists in a straightforward way of acquiring information through a harmonic combination composed of points, lines, circles, slots, and words. This combination must summarize the most fundamental ideas to allow a deeper understanding level and generate knowledge about a subject [36], [37]. Visual components are combined with graphic support that displays clear, objective, and coherent information of iconic origin; the form of presentation leads to a panoramic detection of a dataset conducing to the interpretation, analysis, and generation of inferences [37], [38]. We illustrate infographics used in the present case in fig. 5 and 6. Fig. 5 summarizes the most pertinent details about the first element, radiation-matter interaction, and fig. 6 about second element, electrical transport mechanisms in materials.

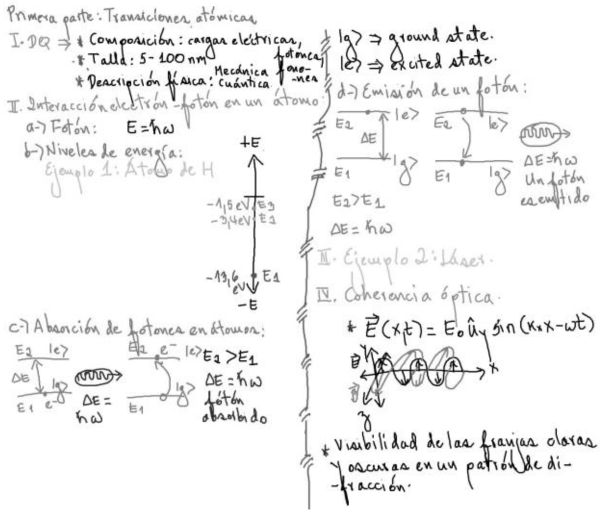

Fig. 5: Infographic regarding the first element, radiation-matter interaction.

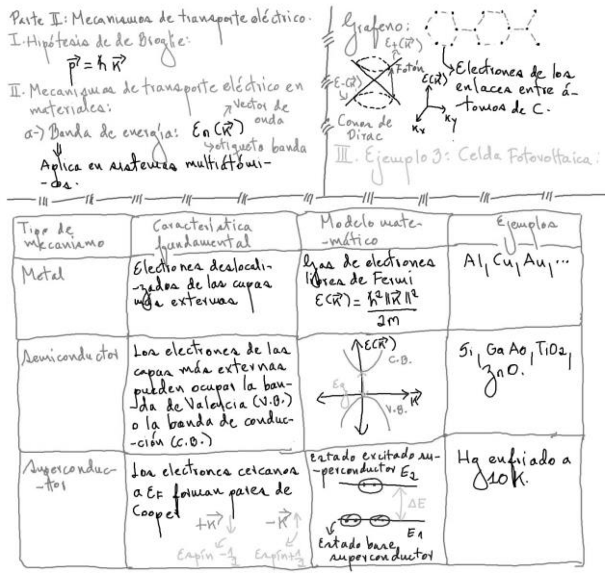

Fig. 6: Infographic regarding the second element, electrical transport mechanisms in materials.

B. Experimental work

Fig. 7 shows the first circuit built in the workshop. Circuit allowed a LED diode to lit thanks to the voltage difference delivered by a photocell. Before connecting to the protoboard, photocell was left directly under the solar light to produce the charges recombination into the semiconductor junctions. Students conceived experimental setup shown in fig. 8 to verify electrical conductivity for varied materials. Light intensity in the bulb was directly proportional to the electrical conductivity for every chosen material. Students could choose between three materials: aluminum (a metal), graphite (constituted by graphene single layers), and NaCl (salt); in the last case, NaCl was diluted in water before. All materials guaranteed a high intensity in the bulb light.

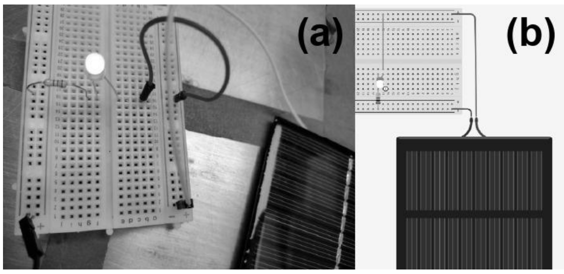

Fig. 7. Electronic circuit including a lighting LED diode. (a) Circuit built in laboratory during the workshop. (b) Schema constructed by using Tinkercad web tool.

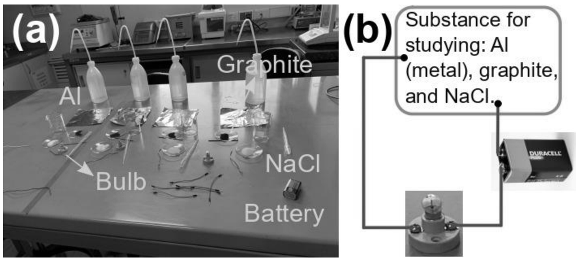

Fig. 8. Experiment to verify electrical conductivity associated with different substances. (a) Materials used in laboratory work. (b) Schema related to the electrical circuit.

C. Proofs and inquires.

To include feedback during knowledge construction process during workshop, we exploited web tool ThatQuiz in the proofs design. ThatQuiz is a web site for teachers and students. It facilitates exercises generation, exams application and development, and fast results visualization. Join for free, in students' case, is not mandatory, all exams are available from the main page. If teachers like to join for free, they can create students' groups and get reports containing their grades, performance, and feedback. Fig. 9 and 10 show a screen capture for one of the exams described in tables 4-7. While fig. 9 shows a general view of the proofs taken by students, fig. 10 presents the view appearing when student completely accomplishes it.

Fig. 9: General view of the diagnostic and evaluative exams.

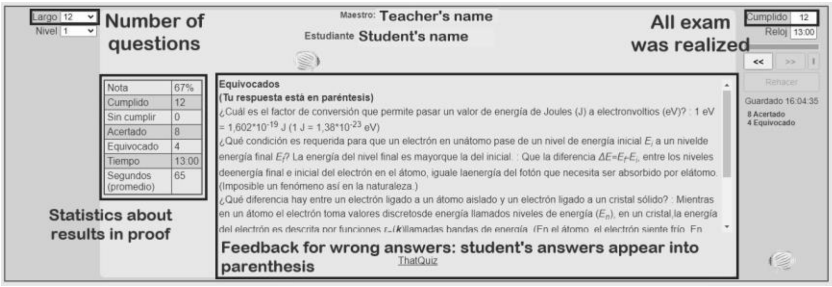

Fig. 10: Feedback and results for the proof presented by students. Screen capture in the graphic appeared when the student completed the exam.

On the other hand, students' proportion (in percentage) for all possible attainable scores in the diagnostic and evaluative tests is shown in fig. 11. Fig. 12 compares average scores obtained by students for the two elements detailed in table 3. All graphics evidence that obtained performance, in the evaluative case, is always better than in the diagnostic case. Likewise, all students answered YES to the IQ4 question in table 8. Nevertheless, realization of quantum devices workshop can be improved. In fact, table 9 shows that only 12,5% of students got a full understanding about fundamental concepts of quantum mechanics (question IQ2), and 25% of students affirmed to be fully satisfied with the development of the workshop (question IQ3). In the last inquiry question (IQ5), students recommend some aspects that should be considered for future versions of the quantum devices workshop, they suggest strengthening the theoretical component (or quantum theory), diversifying didactical materials, checking again the topics, extending the during in time of the workshop, proposing class problems for improving mathematical analysis tools, and exploiting more widely the technological and multimedia resources.

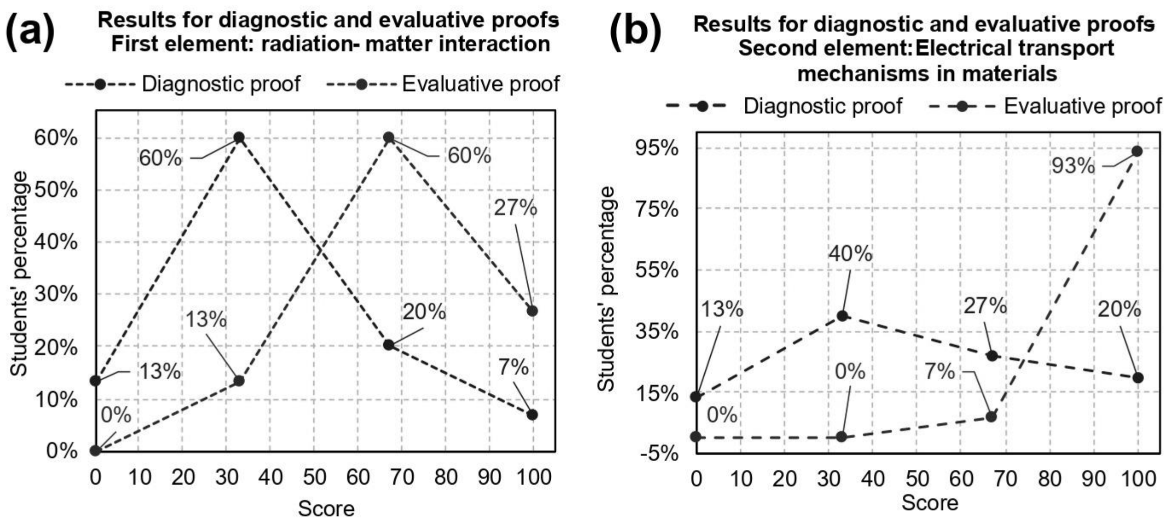

Fig. 11: Comparison between the results in the diagnostic and evaluative proofs for all possible attainable scores 0, 33, 67 and 100 points. (a) first element, radiation-matter interaction, (b) second element, electrical transports mechanisms in materials.

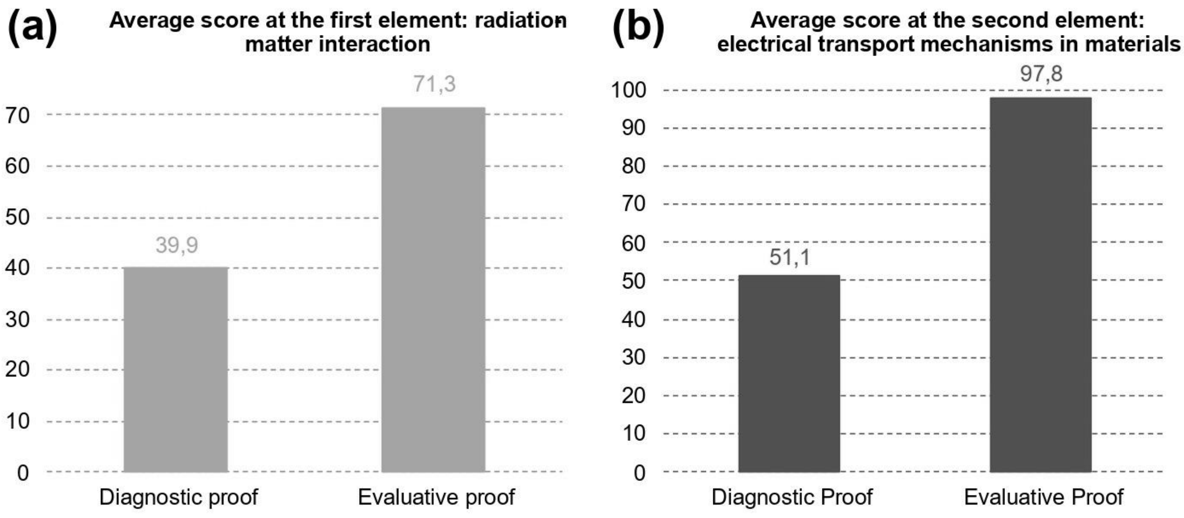

Fig. 12: Comparison of the average scores between the diagnostic and evaluative proofs. (a) first element, radiation-matter interaction, (b) second element, electrical transports mechanisms in materials.

Table 9. Comparison of the students' proportions, for each answer (or grade), in the satisfaction inquiry. Concerning questions are IQ1, IQ2 and IQ3 of the table 8.

Inquiry question	**Students' proportion (in percentage, %) per grade**					
	1	**2**	**3**	**4**	**5**	**Total**
IQ1	12,50	18,75	43,75	12,50	12,50	100
IQ2	-	-	25,00	62,50	12,50	100
IQ3	-	-	6,25	68,75	25,00	100

CONCLUSIONS

We developed a didactical strategy for improving understanding level of the quantum physics concepts. Experimental work was animated around the quantum devices with high potential for the development of clean energies in concordance with the seventh Sustainable Development Goal. Quantum devices used during the workshop were laser, LED diode, and photocell; they also were exploited for introducing the most fundamental concepts of quantum physics. We divided the theoretical component at the workshop into two main elements, the first, radiation-matter interaction, and the second, electrical transport mechanisms in materials. Despite the satisfying results gotten in evaluative proof, at the end of the workshop, and the general success in its realization, students recommended some aspects that should be considered for future versions. These suggestions may be discussed into a curricular framework to motivate the research works in quantum physics topics contributing to a higher sensibilization about importance of clean energies. The workshop treated in the article strengthened interinstitutional exchange between the two participating universities.

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