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A CONCEPT MAP DESIGN FOR IDENTIFICATION AND CORRECTION OF STUDENTS' MISCONCEPTIONS ABOUT WAVE-PARTICLE DUALITY OF LIGHT

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Abstract. The concept of wave-particle duality plays a central role in explaining quantum phenomena. It is often cited as the symbolic barrier that must be overcome to develop the abstract thinking necessary to understand these phenomena. Scientific research shows that a large part of students' difficulties in understanding this concept is due to their subjective perceptions (misconceptions) that are incompatible with the scientific ideas. To increase the effectiveness of teaching the concept of wave-particle duality, research on the misconceptions and a renewal of the didactic tools are needed. This article presents a list of typical misconceptions about the wave-particle duality of light that are described in the scientific literature. We propose the design of a concept map for the wave-particle duality of light, which can be used both as a teaching resource and as a tool for identifying the misconceptions of students from different educational levels (mandatory and additional physics education in secondary school and education in physics and engineering in undergraduate programs). This paper and the literature cited in it can be used as a basis for pedagogical studies of students' conceptual difficulties about wave-particle duality of light.

Keywords: wave-particle duality of light; misconceptions; concept map

1. Introduction

The conceptual approach to quantum mechanics allows for the introduction of its foundations at lower educational levels. In many countries around the world, including Bulgaria, the experimental foundations of quantum physics are part of the physics curriculum in secondary schools. The aim is to show how the need to explain a number of experimental facts has led to the creation of quantum theory, which is a higher level of knowledge than classical physics, because it establishes the limitations of many classical conceptions.

The lack of visibility of quantum mechanical objects (wave – particle) and the description of their behavior, related to the introduction of the concepts of probability, uncertainty and superposition cause methodological difficulties in introducing the basics of quantum physics in secondary school.

According to (Bransford et al., 2000) students often have misconceptions about physical properties that cannot be easily observed. Their misconceptions are prejudices acquired from everyday life experience. They are contrary to generally accepted scientific theories. Misconceptions in physics give seemingly correct explanations for correlations and phenomena, but they are based on superficial considerations and are not actually in accordance with the experiment.

The concept map is a diagram that consists of concepts and ideas written in ellipses, circles, rectangles, or squares (called nodes) joined by labeled lines or arrows (called arcs) showing relationships between the concepts. Two concepts connected by linking words indicating the relationship between them form a proposition (Novak, 2006). A concept map can be in hierarchical, cluster, or chain form. The concept mapping is based on the constructivism. It is an active learning method because it requires students to synthesize information, organize concepts into hierarchical structures, and make connections between them. Concept mapping facilitates the organization of knowledge in a specific area and can be used both to encourage active learning and as an assessment tool (see for e. g. (Djanette & Fouad, 2014) where it was used to identify misconceptions about light among students, studying geometric optics). In physics education, it can be used as a multifunctional tool (Utami et al., 2022).

The understanding of the quantum model of light as a system of photons involves a high level of abstract thinking, and the use of various visualization tools would make it easier.

This article presents a list of typical misconceptions about the wave-particle duality of light that are described in the scientific literature. A concept map design for the wave-particle duality of light is proposed. It can be used both as a teaching resource and as a tool to identify misconceptions.

Some quantum properties of light, reflected in the concept map, are briefly presented in Section 2. Typical students' misconceptions about the duality of light are discussed in Section 3. In Section 4 a concept map for the dualism of light is proposed and the methodology of its construction is described. The main points of the paper are summarized in the Conclusion.

2. Quantum properties of light

According to quantum theory, light is a system of photons. If the intensity of the light is greater, it contains a greater number of photons. The photon exhibits properties of both a wave and a particle, but not simultaneously. Like a wave, the photon is characterized by a frequency ν and a wavelength λ, and like a particle, it is a discrete object with a definite energy E and momentum of magnitude p, defined by the equations

$$E = h\nu \qquad (1)$$

and

$$p = \frac{h}{\lambda}, \qquad (2)$$

where $h = 6.62607015 \times 10^{-34}\,\text{J.Hz}^{-1}$ is the Planck's constant.

From the ratio $E = mc^2$ and the photon energy (1), the photon mass is obtained $m = h\nu/c^2$. This mass is due to the fact that the electromagnetic field has energy. The magnitude of the photon's momentum is $p = mc = h\nu/c$, whence it follows that

$$E = pc. \qquad (3)$$

From (3) and the expression for the energy of a free relativistic particle, $E = c\sqrt{p^2 + m_0 c^2}$, it follows that the rest mass m_0 of the photon is zero, i.e. the photon as a "particle" in the electromagnetic field exist only in motion.

The photon is electrically neutral and has spin 1. Its axis of rotation is parallel to the direction of movement. It is this property of the photons that supports the polarization of light.

The photon's motion obeys Heisenberg's uncertainty principle, which is a mathematical expression of the wave-particle duality. For the photon it is impossible to simultaneously accurately determine the values of the coordinate and the corresponding component of the momentum, because in accordance (2), the momentum of the photon is related to its wavelength, and to speak about a wavelength at a given point in space is meaningless.

When describing the phenomena of interference and diffraction of light, we consider the photon as a wave, and when describing the interaction of light with matter (emission, absorption and scattering) – as a particle. In the processes of interaction between a photon and an electron, the laws of conservation of energy and momentum are valid. In these processes, one electron interacts with only one photon. When a substance absorbs a photon, all of its energy is transferred to one electron. Since the energy of the photon at low frequencies (e. g. in the infrared region) is small, for this range of frequencies the corpuscular properties are weakly manifested, while the wave properties of the radiation are strongly manifested. At high frequencies (when the energy of an individual photon is relatively large) the corpuscular properties of light must be taken into account.

Let us note that some conclusions of the classical electromagnetic theory of light can be drawn as special cases of the more general quantum theory. Thus, for example, at sufficiently low frequencies, for which $h\nu << kT$ ($k = 1.380649 \times 10^{-23}$ J/K is the Boltzmann constant, T – the absolute temperature of the radiation), Planck's formula for the spectral energy density of the equilibrium radiation gives the Rayleigh-Jeans law associated to the ultraviolet catastrophe.

3. Typical student's misconceptions about the duality of light

In the last few decades, the understanding of the nature of light by students of different educational levels has been actively investigated. The results show that the learners have different ideas and most of them are inaccurate in relation to those generally accepted by the scientific community.

The main topics used in the scientific literature to investigate students' conceptual understanding of the nature of light are: (a) the properties of the photon (Ireson, 2000; Olsen, 2002; Greca & Freire, 2003; Hubber, 2006; Dutt, 2011; Özcan, 2015); (b) the double slit experiment (Johnston et al., 1998; Ireson, 2000; Dutt, 2011); (c) the photoelectric effect (Özcan, 2015, Taşlıdere, 2016; Namgyel & Buaraphan, 2017).

According to (Krijtenburg-Lewerissa et al., 2017) the existing students' misconceptions about the duality of light can be grouped into three categories: (1) classical description, in which students describe the photon exclusively as particle or wave; (2) mixed description, in which students see that the wave's and the particle's behavior coexist, but still describe single photon in classical terms; and (3) quasi-quantum description, in which students understand that the photon can behave as both particle and wave, but still have difficulty describing events in a non-deterministic way. These categories all depend on the extent to which students hold on to classical thinking. **Table 1** presents the students' misconceptions about the wave-particle duality of light, divided into these three categories.

Table 1. Typical misconceptions about wave-particle duality of light organized into three categories (the data are taken from (Krijtenburg-Lewerissa et al., 2017))

	Classical description	**Mixed description**	**Quasi-quantum description**
Photons	*The photons are depicted as classical particles.* *The photons have definite trajectories.* *The light always behaves like a wave.*	*The photon follows a definite sinusoidal path.* *The equations of the properties of light also apply to electrons.*	*The photons are waves and particles simultaneously.*
Double slit experiment	*The light has no momentum.* *The photon deflects at a slit and subsequently moves in a straight line.*	*No interference pattern appears with single photons.*	*There is no relation between momentum and interference pattern.*
Photoelectric effect	*Energy is transmitted by wave fronts and more wave fronts cause more energy.* *The intensity of light influences the energy transferred to a single electron.*	*Light collides with electrons.*	

It has been observed that some students mistakenly think the photoelectric effect results from the ionization of atoms through interaction with light (Taşlıdere, 2016). Another misconception is that light chemically interacts with the electron (Oh, 2011). Sometimes, the distinction between the intensity and frequency of light is not made, and it is mistakenly believed that the number of photoelectrons depends on the energy of the photon (Taşlıdere, 2016).

Various research tools have been developed to diagnose students' understanding of the nature of light: questionnaires (Ireson, 2000; Olsen, 2002; Özcan, 2015), a three-tier multiple-choice diagnostic test (Taşlıdere, 2016), conceptual assessment test (Namgyel & Buaraphan, 2017), concept maps (Djanette & Fouad, 2014). In (Djanette & Fouad, 2014) concept mapping has been shown to be a very effective way to reveal students' misconceptions about geometric optics.

4. Methodology for creating the concept map

Here we propose a visual representation of the concepts related to the dualism of light and the relationships between them in the form of a concept map (see Fig**.** 1) with a hierarchical structure, i.e. designed to be read from top to bottom. Its composition can be described in the following five steps:

Step 1: Formulating the main question "What is the corpuscular-wave dualism of light?". It is placed at the top of the concept map and serves as a starting point.

Step 2: Making a list, called a parking lot, containing the key concepts related to the wave-particle duality of light. Some concepts may remain in the parking lot after the map is constructed if no connection is found between them and concepts from the map.

Step 3: Arranging the concepts from the list in a hierarchical structure, with the most general concept placed at the top of the map and the most specific – at the bottom. The concepts are written in an ellipse, circle, rectangle or square. Two parallel hierarchical structures are built here, corresponding to both particle-like and wave-like behaviors of light. These are the nodes of the concept map, see Fig. 1.

Step 4: Identifying relationships between the nodes of the concept map (the arrows in Fig. 1).

Step 5: Putting the most accurate linking words that describe how the concepts are related to each other.

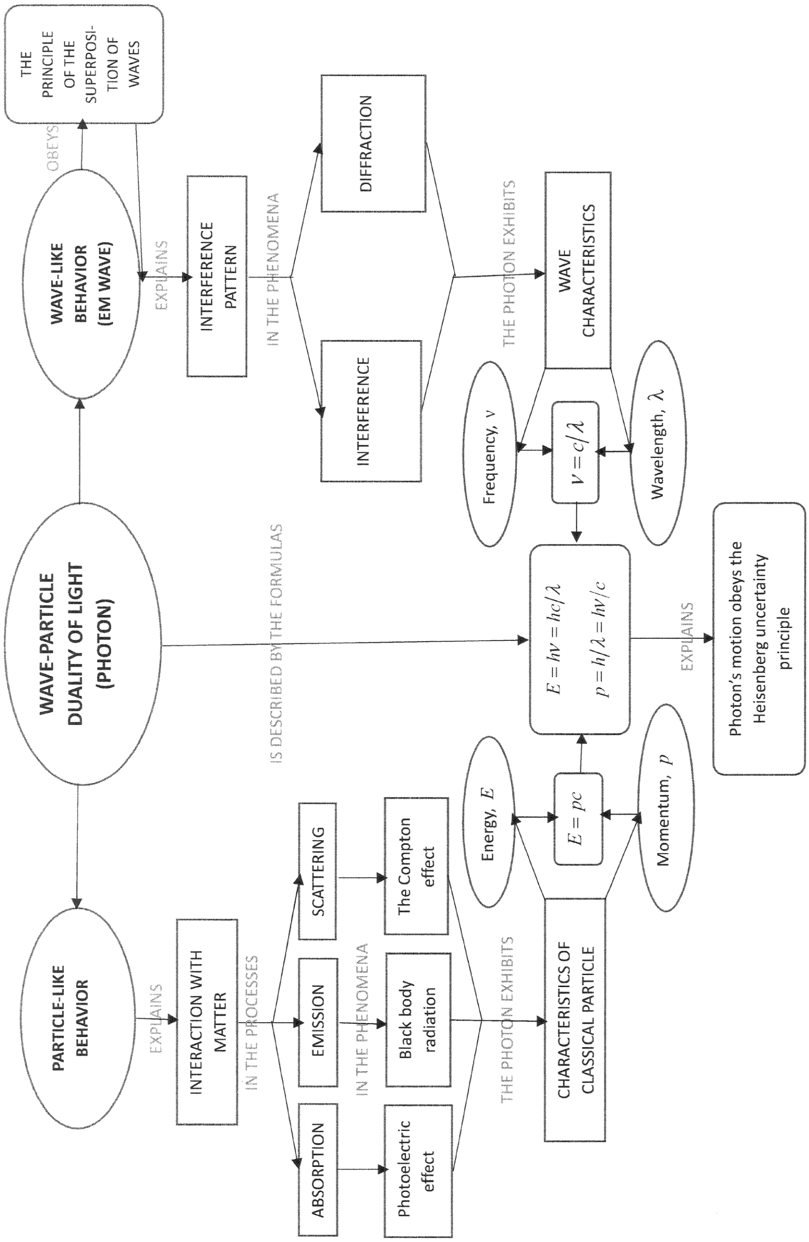

Figure 1. A concept map of the wave-particle duality of light

5. Conclusion

Based on the scientific literature, we present a list of typical misconceptions about the nature of light and propose the design of a concept map for the wave-particle duality of the properties of light. Concept maps have been successfully used to make knowledge structures visible.

The proposed concept map can be used both as a teaching resource and as a tool to identify misconceptions about the corpuscular-wave dualism of light of learners from different educational levels (mandatory and additional physics education in secondary school and physics and engineering education in undergraduate programs).

In summarizing the topic of the corpuscular-wave dualism of light, the concept map (Fig. 1) can be used as a teaching resource. It can be constructed under the guidance of the teacher, following the steps in Section 4. Another option is for learners to create a text based on the concept map. This would help them organize their knowledge on the topic more easily.

In investigating misconceptions, learners can be given the concepts from the parking lot (Step 2) and asked to build the two hierarchical structures (Step 3), connect the concepts (Step 4) and fill the linking words in (Step 5). Another option is to provide the learners with the concept map (Fig. 1) with some missing concepts in the nodes and some missing linking words and ask them to fill them in. An innovative approach to identifying misconceptions is the use of a concept map (Fig. 1) with embedded errors, i.e. with displaced concepts and/or linking words. Such an approach has been used to identify misconceptions in molecular biology (Correia et al., 2020). In this case, the students' task is to find the errors hidden in the concept map.

More concepts and new connections can be added to the proposed concept map, Fig. 1, and also only parts of it can be used, depending on the goals and the educational level of the learners.

The use of concept maps in education allows students to more easily organize their knowledge, and teachers to work at the level of knowledge reorganization.

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