An instructional method, based on POE (Predict-Observe-Explain), for teaching two basic wave properties and the wave nature of light.

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Abstract. This work presents a series of lessons containing didactic experiments, as well as the related educational research. The series concerns the instruction of prospective primary school teachers who possess a weak Physics background. The main topics of instruction are: basic concepts of wave behavior (mainly interference and diffraction), as well as the wave properties of light. This instruction is based on POE (Predict-Observe-Explain) techniques. It constitutes the basis of a broader effort in the making, which aims at teaching future teachers about wave properties and wave-particle duality. The benefits of teaching such notions of waves to teachers are examined, the learners’ previous knowledge and their views are scrutinised, and their learning progress is monitored. As a further step, the overall outcome of the improvement of learners’ knowledge regarding the given concepts is examined, using educational research tools.

Keywords: Teaching, wave properties, wave-particle, POE.

1. Introduction
In this work, we present a didactic methodology for instruction about two basic wave properties: interference and diffraction, and – through them – the instruction about the wave nature of light.

An experiment-based series of lessons was conducted within the framework of a broader research project aimed at investigating whether it is possible to teach basic Quantum-Mechanical concepts, with a focus on wave-particle duality, electron diffraction and wave properties of matter, to prospective primary education teachers (undergraduates and postgraduates, aged 18-26, of the Department of Education).

A great deal of research has been done in the past into the ability of individuals both of the broader public – i.e. not scientists – and undergraduate Science students to conceive the wave properties of light and matter [1], [2]. These research studies have generated significant results.

Aside from this, basic educational research has been done on how students conceive and build representations of wave-particle notions in Quantum Mechanics [3]. As one of the bases for understanding Quantum Mechanics, teaching the wave-particle duality of matter is considered to be of high educational importance and, as the literature shows [4], [5], it poses many difficulties and has been considered under the light of various proposed methodologies.
The relative innovation of the current research is – we believe – that it addresses future primary school teachers, who usually possess a weak background in Maths and Physics. Furthermore, through the didactic experiments of this project, instructional methods such as POE [6] are tested and refined.

As mentioned above, the ultimate goal of the broader research project – of which this current study forms an initial part – is to construct and evaluate a didactic sequence concerning:

- the wave properties of matter
- the wave-particle duality.

In order to address this, our team decided that two basic didactic strands should initially be constructed. The first should address the notion of basic wave properties that distinguish waves from material objects and particles moving through space. The second strand should address the notion of the wave nature of tiny entities, which cannot be observed by human senses.

In this work it was chosen to teach about the first strand, extending it with the wave nature of light, with the envision that, during the second strand we could continue with the particle nature of light, its dual nature and the analogues double nature of other more “exotic” entities, like electrons.

The three main properties that allow a wave – such as light – to be detected are: diffraction, interference and polarisation. However, it was decided that the most prominent and obvious proof of light as a wave was Young’s double-slit experiment. This was historically the first proof of light as a wave in modern scientific history. The effects of this experiment are clearly visible to the eye; the resulting light patterns are noticeably larger than the initial beam’s diameter, and the distance between the two slits can be easily conceived. It is thus a clear illustration of light as a wave, which allows for a concrete explanation. Moreover, an analogous “double-slit” experiment of diffraction using surface water waves can be easily conducted with the aid of an experimental arrangement. It was concluded that this would make it “clear” to students how the phenomenon functions, giving the opportunity for the teacher to provide scaffolding for the explanation of the initial experiment. Polarisation, on the other hand, needs specific lenses which, although in everyday use (e.g. in sunglasses), are not clearly understood, as regards their function, by the students; it is not possible for someone to see the filter that creates vertical openings for light on sunglass lenses. On the other hand, two slits can easily be created in a piece of paper (something clearly visible) using a razor blade, or by using other simple materials, such as a fine comb partly covered with two pieces of tape so that only two slits are left open.

Thus, it was decided that Young’s experiment would be replicated for the instruction, and the focus would be on the two properties of diffraction and interference on which it is based.

Since this didactic sequence was designed to address learning subjects who have a rather weak background in Physics and Mathematics, the objectives were to teach the aforementioned aspects of waves with the following stipulations:

- the use of equations and mathematical formalism would be avoided
- experimental arrangements would be as easily understood by students as possible.

As a basis for the overall research, a research methodology carried out in Scandinavian schools was used [7]. In this research, students from various upper secondary schools in Norway answered a questionnaire comprising both closed- and open-ended questions. These questionnaires concerned understanding of wave-particle duality, and were delivered after the students had been instructed in Quantum Mechanics in school. The results, however, were not encouraging.

Additionally, our methodology also incorporated several elements of a teaching methodology known as PEF (Projeto de Ensino de Física, Project of Instruction in Physics), which originated in Brazil in the ’60s [8]. This method is based on teaching with the help of experimental equipment and technological devices [9].

Thus the main research aim was that, through the use of methods such as POE and elements of PEF, students with very weak Physics’ backgrounds could learn about wave interference, wave diffraction and the wave-particle distinction.

In a previous stage of our research [10], before conducting the didactic intervention presenting here, a questionnaire was completed by a larger sample (N=38) of undergraduate and postgraduate students. From their answers, it was determined that the students generally:
referred to light as being either solely a wave or solely composed of particles, depending mainly on the source, with only six among them referring to its dual nature
• were not capable of proposing an experiment to reveal the nature of light
• found it difficult to describe even simple wave properties, such as interference, using drawings and/or text
• drew light beams as though they were passing through either small or extremely small slits in exactly the way that the slits allowed: i.e. the waves either propagated in full accordance to the slits’ size and shape or, in cases where the slit was very small, did not pass through at all. In other words, the students did not see alternative patterns of propagation through the slit.

These initial findings (although expected) were a strong indication that the didactic experiments and the lessons should be kept as simple as possible, in order to provide scaffolding for students.

2. The Sample and the Research Method
The sample for this research consisted of N=14 undergraduate and postgraduate primary education students (prospective teachers). Nine of them were between 20-21 years old (2rd or 3rd year at the Department), and four of them were between 23 and 28 years old (postgraduate students). All students volunteered to take part. Physics and sessions in the Physics’ laboratory were obligatory as part of their second-year studies at the Department of Education – yet none of the students had been taught wave interference and diffraction. A special feature of the sample is that all of them had a specific interest in the didactics of Physics. However, their Physics and Mathematics backgrounds were very poor since they came, in their vast majority, from theoretical orientations. As a result, they had not received a thorough scientific or mathematical education during their school years.

The ultimate goal was to investigate whether and how it is possible to teach the wave nature of light “qualitatively” – in other words, without strongly featuring mathematical formalism.

The method adopted in this research project approximates the characteristics of a case study [11], using participatory observation techniques [12] in order to study the development of our didactic intervention as directly and in as much depth as possible. More specifically, POE-based lessons were conducted with small groups of students (2-4 students in each group), so that the teacher/researcher could observe and guide the construction of knowledge in an interview-like setting. The recordings of these lessons, the field notes that the teacher/researcher kept and the drawings and notes made by the students during this process, together with the pre- and post-teaching questionnaires completed by the students, comprise the empirical data collected by this research.

Qualitatively comparing the current method with other methods used to experimentally teach students about interference, diffraction and the wave-particle properties of light [2], [13], it can be said that here we have a more descriptive and qualitative assessment of what the sample learnt (drawings, oral interviews, etc.) and that – naturally – we have avoided mathematical formalism and “heavy” Physics terminology.

2.1. Objectives of the research / Research questions
In this article, the teacher’s field notes are analysed, as well as the pre- and post-instruction questionnaires, in order to investigate the following research questions:

A. What do students know about the dual nature of light?
B. Is it possible to teach students about diffraction and interference with the aid of POE techniques and with simple experimental arrangements and computer simulations?
C. Do students make use of the above two properties in order to prove the wave nature of light (in the beginning and at the end of the didactic intervention)?

2.2. The didactic approach
As mentioned above, this series of lessons was designed according to the POE method [6], and was implemented in four stages as described below:
2.2.1. *Stage A.* The main objective was to provide the students with the notion of diffraction and interference as the criteria for distinguishing between moving material objects (including beams of particles) and waves propagating in space.

Tools and materials used included: the “ripple tank”, a soft spring, a water gun, salt, paper, plastic plates, paper scissors and cardboard.

Initially, the instructor asked the students to distinguish, in advance, which of the following were moving material objects and which were propagating waves: (i) salt pouring from a pot, (ii) a water jet directed towards a cardboard screen, (iii) a spring pushed to move along a desk (from one side of the desk to the other), (iv) transverse and longitudinal waves created on the spring by the instructor/researcher, and (v) water surface movement in the “ripple tank” created by falling water drops.

2.2.2. *Stage B.* Students then observed and described plane waves on the water surface with the aid of a “ripple tank” experimental arrangement, as depicted in Figure 1. This generates water waves, and illustrates interference and diffraction phenomena among them.

![Figure 1](image.png)

**Figure 1.** Experimental arrangement for the production and study of interference and diffraction in water waves (called: “ripple tank”).
Specific Model Used: PASCO WA 9773.
Borrowed from: The Department of Physics, School of Applied Mathematical and Physical Sciences, National Technical University of Athens, Greece.
Credit to: Professor Emeritus Rosa Vlastou-Zanni.

Important “thinking tools” – namely, a drawing of a wave from above and from the side, illustrating wave crests and wave troughs, wave front, wavelength, as well as a light ray – were distributed on paper or clarified at this point. These tools are depicted in Figure 2.
Following that, the students were asked to predict and then carry out an experiment on what happens when a slit is created by two barriers inserted in the ripple tank and, furthermore, how the slit width or the wavelength influences diffraction. Images of this part of the experimentation are depicted in Figure 3.

In the same way, the students predicted and then experimented with the interference of two new waves produced by the two slits, with the arrangement again depicted in Figure 3. With the aid of photos taken by their smartphones and a PHET Colorado simulation, they were able to better observe the patterns on the water surface.

In the final two steps, students were asked to draw the phenomena as observed from above and/or a side view, in order to explain their predictions and interpret / better understand their observations, using all the previously acquired “thinking tools”.

Finally, with the aid of paper, plastic plates, combs, scissors, a water gun, salt and water, they started to recognise diffraction and interference as wave properties and as the criteria by which to identify waves.

2.2.3. **Stage C.** Here, the main goal was to help students identify light as a wave, through experimentally testing diffraction and interference.
Tools and materials used: a two-slit barrier (created from a fine comb and tape), 3 laser pens (2 green, 1 red), small lamps, 4.5 volt batteries, plus all the materials that already existed in the laboratory from stage A. The arrangement with the green laser beam is depicted in Figure 4.

Figure 4. Green laser light incident on a diffraction arrangement with slits. Left: Side view. Right: Back view (showing the screen opposite).

In this stage, students were initially asked to try out the new materials, and were given safety instructions about the use of the laser sources in accordance with the laboratory literature [14].

After that, the students were asked to justify the notion that light is a wave. Almost everyone (13/14) on the questionnaire had referred to the wave nature of light. Therefore, they were asked to explain what they mean when they claim that light is a wave. The teacher reminded them of the two criteria they discovered in stage A, in case they did not propose them themselves. Students then tried to draw, on paper, images of light propagation and light diffraction, and to clarify their drawings. Indicative samples of the students’ efforts are shown in Figures 5 and 6.

Figure 5. A student’s representation of the propagation of the light wave stemming from a laser device and from a lamp, from different hypothetical viewpoints. The word above is “laser” and the word below is “little lamp”

Figure 6. A student’s schematic representation of the diffraction pattern of light created by two small holes (double-slit). The word above is “darkness” and the word below is “light”.

2.2.4. Stage D. Afterwards, the students were asked to carry out the experiments with laser light – with the aid of the instructor – with the aim of depicting light diffraction and interference. Images taken during these experiments were photographed and are given in Figure 7.
Figure 7. Diffraction patterns of green and red laser light beams.
Left: light incident on a diffraction arrangement with two slits (made by a modified fine comb).
Right: light incident on a diffraction arrangement with two slits (made by a modified razor blade).

The experimental arrangement with the laser light and the razor is based on Wojewoda [15]. Students were further asked here to recognise and interpret what they observed, (i) with the aid of the “thinking tools” that they acquired in stage A and (ii) in analogy to the water surface waves of the previous stage.

In this fourth stage, the teacher/researcher introduced the depiction of light as an electromagnetic wave. The learners were asked whether this was familiar to them, and how they understood it. They were asked to compare this nature of light with the material waves they had identified on springs and water in the previous stage. Other materials already in the laboratory (e.g. magnets and one-cent coins) were occasionally used in order to make notions of magnetic and electric fields better understood by the students.

3. Results and Discussion

As mentioned before, some days before the first lesson, students had completed a questionnaire (pre-test). Two and a half months after the lessons took place, the students completed an analogous questionnaire (post-test).

The pre-test consisted of two parts. The first part (part A) comprised 5 questions on more general and basic concepts such as the nature of light and the concepts of wave and wave length $\lambda$. Part B comprised 9 questions that asked students to make predictions for several experiments concerning waves. This test was the same as that which was used in the previous part of our broader research, as explained in the introduction section.

The post-test consisted of three parts. The first part (the introduction part) was handed to students before the other two parts. It consisted of one question only, and this concerned the nature of light. This part was given to students separately as the following parts accepted the wave nature of light as a given – and, in order to properly investigate the results of the didactic experiments, we did not want students’ answers to be affected by information provided in later questions.

In the second part (named part A, with 4 questions), students were asked about basic notions such as light wavelength and its wave nature; in the third part (named part B, with 9 questions), they were asked about the results of experiments concerning waves (both surface water waves and light).

The three questions from each test that were analysed in order to answer the basic questions of our research – the Research Questions (sometimes referred to here as “RQ”) – are described here, in this Results’ section.

The other questions, along with the interview recordings, will be analysed in order to provide better understanding of the elements of our didactic experiments which were successful and those which need to be revised.
Concerning the first research Question (RQ), i.e. A, a first comparative result is shown in Figure 8. The students correctly referring to light as having a dual nature in the pre- and then in the post-test are presented. The students were asked about various sources of light.

![Figure 8](image)

**Figure 8.** Numbers of students that – correctly – referred to light as having a dual nature, in the pre-test and the post-test

More pertinently, since this didactic intervention focused specifically on the wave nature of light specifically, the numbers of students who referred to this before and after the intervention is depicted below in Figure 9 (regardless of if they mentioned the particle nature).

![Figure 9](image)

**Figure 9.** Numbers of students that referred to light as a wave, in the pre-test and the post-test.

However, in the explanation that they were asked to give for their choices, both in the first questionnaire (pre-test) and in the second (post-test), the results showed that they either did not answer at all, or resorted to tautologies such as, “as we know, light has a dual nature”.

As far as the second RQ (B) is concerned (“Is it possible to teach students about diffraction and interference with the aid of POE techniques and with simple experimental arrangements and computer
simulations?" the results were varying. Investigating the teacher’s field notes and the relevant questionnaire, which was the same in both the pre- and post- tests (Fig 10), the attempt was to see whether the students could foresee and latter describe the evolving interference and diffraction patterns.

Figure 10. The rubric says: “Question 25: I shine a laser at a thin piece of paper or other material, in which I have made two small, thin slits with a razor (so that light falls on both slits, as in the diagram). What do you expect to see on the wall? Draw and describe.”

According to the teacher’s notes, all the groups managed to complete the lessons and correctly recognise the pattern created by the double-slit experiment as being a result of wave interference.

However, according to the pre- and post- questionnaires, not all students seemed to have fully assimilated this knowledge. The figure 11, that follows depicts the students’ answers regarding the projection/patterns seen on the screen during the double-slit experiment, both before and after the intervention:

Figure 11. Numbers of students describing various patterns on the screen in the double-slit experiment with light. Columns on the left: pre-test. Columns on the right: post-test
In Figure 11, green indicates those who drew (and/or described) the interference pattern. Red depicts those who drew (and/or described) two light lines, while blue depicts one who drew light as being diffused by the slits. Orange depicts those who drew other irrelevant patterns.

As far as the third RQ (C) is concerned (“Do students make use of the above two properties in order to prove the wave nature of light in the beginning and at the end of the didactic intervention?”), the students’ answers in the pre- and post-test questions are depicted in Figure 12.

On the pre-test question, students were asked to design an experiment proving their answers to question one, in which they had to express their opinion about the nature of light coming from different light sources; at the post-test question, the wave nature of light was taken as given, and students were asked to describe an experiment proving it.

![Graph showing numbers of students proposing each experiment](image)

**Figure 12.** Numbers of students proposing each experiment as the most proper for revealing the wave nature of light. Columns on the left: pre-test. Columns on the right: post-test

In Figure 12, blue depicts those who did not propose anything, while yellow shows those who proposed the double-slit experiment. Orange indicates those who proposed something similar to diffraction, involving light passing through one slit, and green depicts one student who proposed to try to achieve interference by using two light beams from two different sources. Red depicts those students who referenced other irrelevant experiments.

4. Conclusions and Implications

As is shown in this work, the intervention seems to have contributed significantly to the number of students who are aware of the dual nature of light. It is important, given the intervention’s focus on the wave nature of light, that almost every student came to recognise this (regardless of the light source).

The fact that they could not give satisfactory explanations is something that should be addressed when designing the next part of the didactic intervention, concerning the particle nature of light. When students have a more integrated picture of the two natures of light, the meaning of this duality must be clarified.

Before the intervention, students did not seem to know about the wave behaviour of light when passing through slits of comparable size to its wavelength. Despite this, one did propose the double-slit experiment in order to prove the wave nature, albeit without describing it. After the intervention, around half of the students (6 out of 14) were able to correctly draw and/or describe the interference pattern
visible on the screen during a double-slit experiment –although many of them (5 out of 14) described diffraction only, and three more gave other irrelevant answers. Bearing in mind that these phenomena were unfamiliar to them, and that two months passed between the didactic intervention and the completion of the post-test, one explanation could be that they returned to their previous ways of thinking about light. Moreover, keeping in mind that, during the intervention, students collaborated with each other and the teacher scaffolded their thinking, it is to be expected that some of them would not fully manage to recall and describe the findings that they achieved during the intervention.

The answers to the question which asked them to propose an experiment in order to prove the wave nature of light are related numerically, as expected, to their answers regarding the previous research question. This indicates that most students understood light diffraction, although less than half of them understood light interference.

Further analysis of the lesson recordings and the students’ drawings and notes can provide better understanding of the difficulties they encountered and the evolution of new concepts and knowledge during the teaching process. This could perhaps generate suggestions for improving the didactic experiment and the didactic approach as a whole.

However, it is worth mentioning that, according to the teacher’s recordings, all students declared that they were happy to approach such notions in a qualitative way, and all stated it was worth receiving instruction in these notions, even though it would not be possible for them to conduct such experiments as primary school teachers. They added that the dual nature of light is mentioned in primary school textbooks, and that these notions are a scientific way of explaining the world – and, therefore, teachers should know about them.

It should be reiterated here that one of the ultimate aims of our research was to teach prospective teachers basic notions of Quantum Mechanics, while making as little use of mathematical formalism and Physics terminology as possible. One notion which was therefore omitted was the wave properties of particles, as seen in, for example, the Davisson-Germer experiment. Our intention is to include this experiment in our instructional research.

Naturally, there are obvious limitations to the current research, owing mainly to the limited size of the sample, the fact that all students involved were volunteers (and thus already had a certain augmented interest in Physics), and the strong localisation of the settings (specific city, specific university, etc.). Nevertheless, we consider the results to have an indicative power.

In conclusion, the first successful step in designing a series of lessons about basic Quantum Mechanics’ concepts, based on the POE method with the aid of computer simulations, was implemented. The refinement of this first unit, as well as the design of subsequent ones, is the challenge that follows.

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