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To cite this article: Pasquale Onorato *et al* 2021 *J. Phys.: Conf. Ser.* **1929** 012056

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A sequence of experiments and models to grasp the strange nature of light

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Abstract We present a sequence of activities designed to stimulate students to reflect on the nature of light and on the different models (ray, wave, classical and quantum particles) used in teaching and learning optics. These activities are also aimed to help students in evaluating the profound meaning of the "correspondence principle" and develop their own views about some aspects of nature of science even if it is not taught explicitly. In fact, optics is a paradigmatic case where different scientific models are proposed in the University (and high school) courses. Even the oldest of these models have non empty domains of validity and both Maxwellian electromagnetism and geometrical optics are largely still used in the Physics curricula. As a consequence students are often puzzled, and think that each of these theories works in a specific domain, without any connection one with the other. Thus we investigate students' mental models of light in different contexts and we show how they develop hybrid models in explaining different phenomena or use models inconsistently.

1. Introduction

Along the physics curriculum, in the University (and high school) courses, students meet at least three different models of light, at three different levels of complexity: light as a ray (geometrical optics), light as a wave (physical optics, or wave optics) and light as a beam of photons (quantum physics).

Since these different scientific models are proposed in the introductory physics courses, many educational papers in the past were focussed on students' or teachers' perceptions about models in optics, also because misconceptions in optics could be related to the underlying models. It was found that students use different, often inappropriate, models in explaining various physical phenomena such as reflection, refraction, diffraction or colour dispersion [1]; students use hybrid models in explaining phenomena related to geometrical and physical optics [2] and often the models used by students to explain these phenomena do not match the scientific models [3]. The majority of studies by physics education researchers were focussed on the wave-ray dichotomy and only recently phenomena, usually explained by a particle model of light, were analyzed [4] with the aim of understanding what mental models students form about the nature of light, and whether students' mental models about light change with the context.

In this work we present an activity sequence in which students are confronted with a succession of phenomena, chosen to be as close as possible to students' daily experience. For each phenomenon students derive a phenomenological law then they build a model.



At each step conceptual change may be stimulated from the observation of the new phenomenon, which will constitute an anomaly compared to the previous model. Thus the development of a new model will be needed.

Even if we do not follow a rigorous historical and chronological path and we do not discuss explicitly the philosophical issues about quantum physics, the proposed sequence is an opportunity for our students to develop informed *Nature of Science (NOS)* views and for us to present them some epistemological issues.

As reported in [5], according to some educators, the disagreement on interpretations is an excellent example of *science in action* [6]: competing scientific theories can exist next to each other as long as there is no evidence favouring one theory over another one [7–10]. Thus, philosophical and historical aspects have to be promoted not only to enhance students’ conceptual understanding but also to serve the more general goal to develop their view on the NOS in the context of the nature of light even if NOS is not taught explicitly.

Moreover while the experimental activities stimulate students to reflect on the nature of light by discussing the different models, we also discuss with them the profound meaning of the "correspondence principle" and its general value and stimulate students to reflect on *The Structure of Scientific Revolutions* [11], the features of the scientific enterprise and the development of scientific knowledge. The proposed sequence is also an attempt at transposing the Kuhnian theory on scientific revolution [11] to science education following the so called “classical approach to conceptual change” proposed by Posner and co-workers [12,13]. This educational approach shows the interconnections between the science’s development and the educational strategies to promote conceptual change based on cognitive conflict and the resolution of conflicting perspective. In Figure 1 we show a schematic representation of the relationship between the Predict-Observe-Explain-Apply strategy (a variant of POE [14]), the basic principles of Conceptual Change and structure of Scientific revolutions.

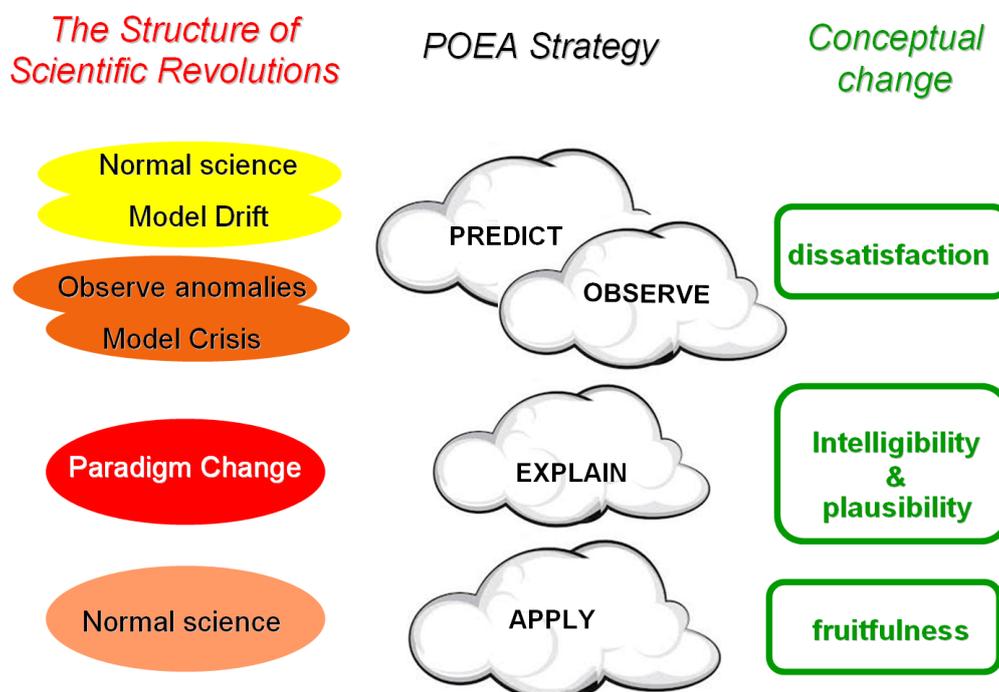


Figure 1. The relationship between POEA strategy, the four conditions in the conceptual change mode (dissatisfaction-intelligibility-plausibility-fruitfulness) and the steps of a scientific revolution according the Kuhnian theory. The steps in each case have to be assumed as recursive phases of a cycle.

Thus, this study attempted to answer following research questions:

- What mental models do students have about the nature of light to explain various phenomena?
- Do students' mental models about light change with context?
- What is the students' general epistemological understanding of the "correspondence principle"?
- What are NOS views after following the activity sequence about Quantum Physics?

2. The sequence of experiments and models

The activity sequence has a total duration of about 12 hours and is structured according to the following steps:

- a) Light refraction, studied quantitatively through Snell's Law, which can be explained through a ray model. This is our starting model that can also be introduced as an *achromatic ray model* where rays can be also seen as beams of particles according a "Corpuscular theory".
- b) Chromatic dispersion as observed in the rainbow. This is an anomaly for the achromatic ray model, therefore it requires the development of a new model: the ray model with refraction index depending on the wavelength of the emitted light. We can here present the Newton model with *colour "corpuscles"* fanning out and travelling with different speeds through a prism. This chromatic corpuscular model represents a different version of the paradigm (the corpuscular model) in order to reconcile it with the observed anomalies
- c) Light absorption, studied quantitatively through Beer's Law [15]; the inadequacy of the previous model is shown. As a result, a new one is needed: the corpuscle model with "*classic stochastic behaviour*". In this case we leave the rigorous historical and chronological path, and following Berberan-Santos [16] we introduce a corpuscular model where the *light corpuscles*, traveling through the material are absorbed and *diffused by randomly distributed scattering centers*. This stochastic model where Scattering events follow the classical probability rules is again an adapted version of the paradigm (the corpuscular model) in order to reconcile it with the new phenomena.
- d) Light interference: fringes in soap films [17] show the inadequacy of the corpuscular model, which is replaced by *the wave model*. To discuss the interference in a more quantitative and detailed way students perform measurements on the interference fringes of a double slit experiment, using a red laser diode. Some simulations were also discussed with students to present the new paradigm, the wave Model.

The approval of the new paradigm requires that the wave model will be able to reproduce the results of the older well-established ray model in those domains where the geometrical optics works. Thus we show how the laws of reflection and refraction follow from Huygens Principle also with the help of some applets, by presenting the correspondence principle for the first time.

- e) Finally the photoelectric effect is qualitatively observed (properly we reproduce the Hallwachs experiment) and subsequently quantitatively studied with two experimental set-up (using the Leybold photocell and the PASCO apparatus). A very appropriate applet is also used to better explain the experiment and to present the Einstein's interpretation. The latter explanation shows students the inadequacy of the wave model in favour of a quantum photon model.

Also in this case we emphasize that the new corpuscular model for the light has to reproduce the results of the older well-established wave model in those domains where the wave optics works. A qualitative explanation of the behaviour of the quantum object is given starting from the sum over path approach [18, 19]. In his first example in the book QED, Feynman [20] considers light reflected from both the front and back surface of an extremely thin glass sheet and explain the interference in terms of sum over paths. This explanation was discussed with students also by showing them a significant simulation [21] able to explain analogously the coloured fringes observed on the surface of the soap film.

Then the single photon and single electron double slits experiments were largely discussed.

Moreover the electron diffraction experiment [22, 23] is presented to show the strange behaviour of light and matter. Thus, thanks to simulations [24] and recorded data from real experiments,

the famous "*Feynman Double Slit Experiment*" for electrons where one electron at a time from the electron gun is fired, and students can observe the build-up of electron positions on the screen.

A short discussion about the wave-particle duality concludes the sequence. In this phase we state the existence of a quantum object having own properties (i.e. following the Feynman's rules) and overcome the duality presenting "*the metaphor of platypus*" from Levy-Leblond ¹ [25].

Each step from a) to e) is characterized by activities where the students are really engaged in performing experiments, simulations and toy models.

During the activities, we discuss with students step by step how the new model is related to the previous one on the basis of the "*correspondence principle*" which denotes the requirement that any new theory reduces to an older theory when it gets applied to the older theory's domain of validity.

Thus each new model must also be able to explain the phenomena belonging to the validity domain of the previous model; this should work up to arrive to a coherent explanation of the whole phenomenology based on the quantum model.

3. Results

The sequence of experiments and models was developed with a group of 35 undergraduate students of the University of Trento (and 20 high school on service teachers). The students had taken university level courses covering the topics of quantum physics, or any other topic related to other aspects of light.

Instrument and procedures The survey method was used in this study. Before, during and after the activities with students we asked them questions aimed at understanding their opinion and general perspective on physics; thus we collected data both from multiple-choice items and interviews. Moreover at the end of the activities we asked a question with drawings and explanations about the double slit experiment.

The questions we pose focus on students' general epistemological understanding of the "correspondence principle". In fact often students conceive physics as a set of disjointed phenomenological domains, to each of which a different theoretical model must be applied [26]. Questions generally involve asking students whether a model of light is able to explain phenomena typically represented with another model, e.g. "*can wave optics explain refraction?*".

Before the activities we ask students to write what they think about what light is, the answers are summarized in figure 2.

¹...the description of quantum objects by a duality between two classical aspects is in fact of limited validity. While it is a very useful point of view for the first contacts with these strange objects, it is by far not sufficient to take into account all the subtleties of their behaviour. Australian settlers, on their first observations of a weird animal, named it "duckmole" on account of its mole-like fur and form and duck-like beak and feet; but duck-mole duality certainly is insufficient for a full appreciation of the specificities of the platypus (which, by the way, already had a name of its own before European scientists came to study it — namely, "mallongong"). In fact, the expression "wave-particle duality" offers not an answer to the question of the nature of physical entities, but asks a question — and a nontrivial one: how is it that quantum objects do appear at the classical approximation either as waves or as particles? Or, more precisely, what are the conditions of validity of these two (exclusive but non complementary!) approximate descriptions? In any case, as an epistemological solution to the general problem of the nature of reality, "wave-particle duality" falls very short of its goal. Quantum Words for a Quantum World (Jean-Marc Levy-Leblond 1998)

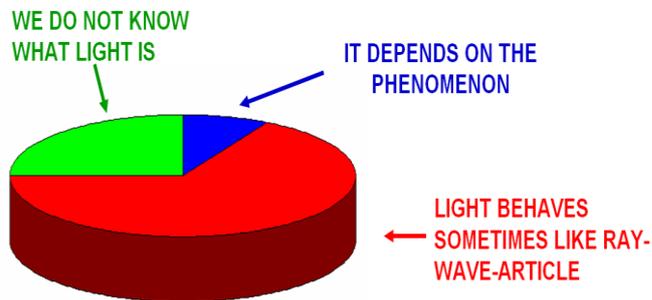


Figure 2. Students' answers to the question "What do you think about what light is"

Results confirm that students are often confused by the use of different models to describe optical phenomena and consider each model as limited to a narrow and specific set of phenomena. The idea of a correspondence principle, requiring that new physical theories do not contradict previous ones, but extend and generalize them, is in most cases foreign to students' thought.

However the main result is that a *stone guest*, the *wave-particle duality*, dominates the learning process. In fact students' difficulties in understanding wave-particle duality hinder the understanding of correspondence principle.

In particular, after the activities, we asked students to draw their mental image of the two main experiments of the sequence the double slit interference (when a laser beam enters a double slit as in our real experiment) and the photoelectric effect. Our results can be compared to the ones obtained by Özcan [4], who investigated pre-service physics teachers' mental models of light in different contexts, such as blackbody radiation, the photoelectric effect and the Compton effect. The study confirmed the hypothesis that students' mental models are context dependent [27, 28], i.e. students may use different, stable, and coherent explanatory schemas when they explain a phenomenon related to the same concept, but they put it forth via different contextual settings. The author of [4] showed that three mental models, which were called the beam ray model (BrM), hybrid model (HM) and particle model (PM), were being used by the students while explaining the behaviour of the light.

In figure 3 top part we report some of the drawings produced by students for discussing the double slit experiment while in figure 3 bottom part we report drawings about photoelectric effect. Our results show that hybrid models are mainly used to explain the behaviour of light before and after the two slits: light is a ray before the slits and a wave after.

The mental models about the photoelectric effect are more manipulated by the different pictures, which students find on textbooks and webpages.

With the aim of analyzing the students' answers collected in some interviews we recall some aspects of nature of science and history of science in quantum physics emphasized by Stadermann et al.[5] as *The role of scientific models*, *the Tentativeness of science* and the *Controversies in science*.

In fact science education research shows that several NOS aspects are particularly relevant for learning Quantum physics, e.g. a student who believes that science provides absolute truth will have problems appreciating the different interpretations of Quantum Physics. Moreover, many concepts in Quantum Physics are indissolubly connected to philosophical, epistemological and ontological issues.

The other stone guests, strong ideas, known from literature are

- "Science is universal, and scientists are absolutely objective. Therefore good scientists always agree. If they don't agree, we cannot trust science"
- "Scientific models represent reality as much as possible. If different models exist, only one can be right."

a scam: the light is neither this nor that or is both this and that. But what problem is there, this opens the mind to the idea that it is not all already discovered, all clear. There is still work to be done... there is no clarity even in the scientific community”

For other students “the stone guest” acts with the NOS aspects cited above to hinder also to the understanding of correspondence principle so that substantially the knowledge of the Quantum World is a big open problem. We asked “... according to the correspondence principle the quantum theory based on photons should also explain all that explained with the wave theory. Do you agree?”

The student answered:

“Yes. And here is a big problem. At the moment I don't know what to say about it, I see it as an open problem. It is probable that I did not understand how things are: it must be so, I have missed something.”

4. Conclusions

We can conclude that, during the activity sequence in which students are confronted with a succession of phenomena and models aimed to grasp the strange nature of light, students developed NOS views, mainly in the context of Quantum Physics, even if NOS is not taught explicitly.

Results demonstrated how these NOS views are context dependent and that students usually employ non-scientific knowledge fragments along with scientific ones when developing mental models related to light. Also the latter mental models are strongly context dependent and students employ different explanatory schemas when they describe a phenomenon related to the same concept, the light, but they put it forth via different contextual settings.

Results demonstrated that students’ difficulties in understanding wave-particle duality hinder the understanding of correspondence principle.

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