The Young experiment as a teaching tool

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Abstract

The Young experiment is one of the leading experiments that clearly show the wave nature of light and at the same time, one can get quantitative results without using complicated calculations. As established by classroom experience, the measurements and the repeating of results leads students to very valuable conclusions concerning the understanding of nature, science and history.

KEYWORDS: Young Experiment, Optics, Interference

1. Introduction

The repeating of historical physics experiments and especially ~~of~~ those that led to the fundamental discoveries in physics plays a leading role in secondary teaching; in many cases even university courses [1, 2, 3]. Their power to deepen understanding might even be higher for those pupils or students that do not follow a scientific course.

Any learning procedure has as a final goal, the understanding of the material taught to the pupils/students. At this point many pedagogical approaches try to give answers. One possible tool, which in our opinion is powerful, is the repeating of selected historical experiments.

Each human society in history has developed a certain amount of knowledge and skills (as a mean in the total population), interacting continuously with scientific thought and tool invention. This means that the people we usually call thinkers, those that make a major contribution in philosophy, science etc. were confronted at each moment with the problems arising within their specific society and level of scientific evolution and tried to give the "best possible answer" in the gnoseological context of their era. Speaking especially for physics now, it is at that point that the concept of historical experiments emerges. We should first define what an historical experiment is. It can be conceived as an experiment that gives rise to a new theory, or solves (or contributes to the solution) of a controversy that existed at a specific time.

When dealing with such an experiment a pupil/student is invited to become restrained by the knowledge existing at the time; that is, to take into account only what was already known at the specific moment just before the historical experiment she/he will deal with. In this case the opportunity is opened for thinking about the conclusions she/he could come up with, if she/he was the one to discover for the very first time the corresponding results.

Based on the previous analysis, our approach is the following: we should first give a brief but clear understanding of the level of comprehension and scientific knowledge at the time of the experiment, then perform the experiment and analyze qualitatively as well as quantitatively the results obtained. After this, try to come to conclusions retracing more or less the thinking path of the scientists of that era. After teaching is completed, an evaluation of the results is of interest. It is, we believe, an issue as important as the first part of the procedure. Statistical results of selected questions can help us to understand the extent of comprehension and eventual misunderstandings of the pupils/students so as to improve the presentation (either experimental or theoretical). At that point we can summarize the above analysis as follows:

The cause of the significant importance of historical experiments is that, once properly introduced to the pupils/students, the latter may come to an understanding of: a) the connection of science and the acquired knowledge level of humanity with the socio-economical environment, b) the real essence of the problem studied and the role it plays on technology and the gnoseological level at which society is, c) the underlying physics and generally the importance of the expected results and d) the evolution of our knowledge and ideas in their recent form.

In such a process students do not gain knowledge, "from nowhere", but they understand the real adventure of the human mind in solving problems and acquiring knowledge. It seems that they will also gain deeper thinking capability and an extra interest in scientific problems. One can easily understand this point if one imagines the completely opposite situation. An experiment among those we defined as historical ones, if presented with few or without any explanations of the corresponding significant importance, means that students do not even see why they are making the effort to learn the experiment. In our opinion this is a total pedagogical disaster. It is thus always important to refer to such experiments, either in a normal course, or separately, to help students in the way described above.

One of the well known historical physics experiments is the double slit Young experiment. It is this experiment that we shall deal with in the present work.

2. The historical context

From the 17th century Newton's personality dominated in physics. His discoveries and ideas governed and any contestation of this was considered almost as a blasphemy. For more than 100 years, until about the end of the 18th century, his idea that light is constituted by particles remained dominant. At this point it is worthwhile giving the main lines of Newton's theory of light [4, 5]. He thought that light is constituted by small particles, very tiny ones that enter the human eye and cause what we call vision. Those tiny particles act like all other material bodies we know, such as stones or billiard balls. Of course a theory has to give an explanation of observed phenomena. Reflection of light is explained the same way as reflection of an elastic body against a wall. Refraction is a bit more complicated. When light particles come from the air into a transparent medium like water or glass for instance, with a velocity that makes a certain angle with the normal to the surface separating the two media, then entering the transparent medium their velocity suffers a change of angle (in fact it becomes smaller) compared to the previous one. In this case the gravitational attraction between light particles and the transparent medium increase the component of the velocity normal to the medium surface but leaves the parallel one unaffected. This explains why the entering angle of the velocity is less than the one with the surface medium but it also means that light should travel inside the new medium at a higher speed which, at that time was not verified. We know now that it is not the case and this is against Newton's theory. Still it is astonishing that Newton also gave an explanation, within the context of his theory, of why light should travel at constant velocity inside a medium: as the surrounding particles of the medium are exerting symmetrical gravitational forces to the light particles, they should give a resultant force equal to zero, as a mean value, at all times. He also gave an explanation of the difference of bending angles when light passes through a prism. He claimed that more massive light particles, those of red light, were deflected less than the lighter particles of the other colors, right down to the smallest of all those of blue color particles. At the end of the 18th century some doubts came up concerning the particle theory. In the context of a particle theory no interference phenomena were conceivable at that time, especially when the particles were considered as classic material particles. Therefore some scientists realized that in order to explain Grimaldi's (1618-1663) observations [6] concerning the diffraction of light, they had to use the wave theory of light. Grimaldi, in his two volume work, published posthumously in 1665, describes phenomena where the rectilinear motion of light beams, refraction and reflection cannot be applied to give an explanation of the experimental facts. He saw that when light passes through a hole the shadow produced is not the geometrical one. There is a clear and not unimportant region where light is present (something like a "brighter region into the geometrical shadow"). Also, near the edges he saw colors. He thus used the term diffraction and rejected the corpuscular theory. He thought of light rather as a fluid like water, where waves analogous with waves in water may propagate. These phenomena were known to Hooke and Newton and they used the term "inflection". Grimaldi's term diffraction is the one that finally survived. Others scientists followed [7] and the most important who investigated diffraction patterns was Fresnel (1788-1827) [6, 8, 9] who gave a full theoretical explanation of Grimaldi's observations.

Fresnel had a supporter, Arago (1786-1853) [6, 9]. They set up and performed a lot of experiments together. Some of them were very simple, but a number proved to be of great importance, because they convinced even skeptics or scientists opposed to the wave theory, that this theory in fact is true. Those experiments were influenced by Poisson (1781-1840) [6, 9], who was one of the greatest French scientists of the early 19th century.

Poisson claimed that - if light has a wave nature – and, in the path of a light beam which emerges from a point source we put an opaque circular disc perpendicular to the beam direction, the waves should come to every point of the circular obstacle with the same phase and thus give a luminous point at the centre of the obstacle's shadow! This (theoretical) result seemed to him completely absurd. But Fresnel with Arago performed this experiment and they observed that this luminous point in fact exists. From this moment, the theory of light's wave nature came to be generally accepted.

The most important conclusion of this event is that we should not ground our considerations and results only in the theory. No matter how obvious or elegant the theoretical predictions might appear, they should be tested through experiment. If this test gives satisfactory results relative to the theoretical predictions the corresponding theory may be accepted and new experiments can be set up. But if the theory does not explain the experimental facts, the theory might be revised or be changed completely. In the case of physics all these possibilities are open.

The wave nature of light can be tested in a different way, by using the interference phenomenon. The most famous experiment is the one performed by Young (1773-1829) [10, 11] who observed light interference when light passes through two narrow slits. Young understood that it is impossible to observe interference phenomena with light coming from two independent sources and for this reason in 1807 performed the following experiment: in a dark room he let sunlight pass through a very narrow hole that he produced with the aid of a very fine needle, thus producing a diverging sunlight cone. In the center of this cone he put a piece of paper about one millimeter in size, thus dividing this beam into two parts. Afterwards he put a screen in the direction of the split~~ed~~ beam and saw interference fringes on it that were symmetrically placed. The central fringe was white. At the edges fringes were colored. The fringes thus produced coincided with the corresponding fringes that Fresnel saw. When Young moved the piece of paper towards the edge of the initial beam the interference fringes disappeared. Young performed many experiments in order to convince himself that this phenomenon appears when the initial beam is divided into two beams.

The simplicity as well as the persuasiveness of Young’s experiment played a very important role in the confirmation of Fresnel’s work concerning the wave theory of light.

The most important advantage of Young’s experiment is that, it can furnish quantitative results with the use of simple mathematics. Fresnel’s diffraction also can give quantitave results, but in this case rather complicated mathematical calculations are needed. The Young interference fringes can be described by a simple theory and be used to measure wavelengths of light with an accuracy of about 1%.

3. The experiment

Repeating this experiment is nowadays a standard procedure which is used in school classes, usually at the final level of the secondary, as at this level students are more mature and able to follow, at least in principle, the mainlines of the experiment as well as the scientific reasoning.

To prepare one of these experimental presentations we performed the Young experiment as follows (students were not present at this stage). The experiment was performed in the laboratory of the European School Brussels III. We will describe the teacher's preparation and then present the part which, at this level, will be presented to the students:

We used as light source a 5 beam He-Ne LASER (figure 1), of 2 mW power and a wavelength of 632.8 nm, as provided by the factory. Actually we take this wavelength as being error free. The same thing holds for the two slits (figure 2) which are at distance of 0,6 mm, as provided by the factory.

Figure 1. The He-Ne LASER we used

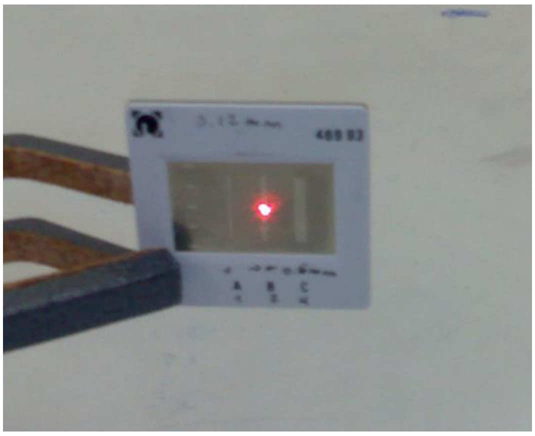

Figure 2. The LASER beam passing through the double slit.

The LASER beam was at a distance of 20 cm from the double slit (figure 3) and the distance of the double slit to the screen (actually a wall) was of $(250,5 \pm 0,5)$ cm. This error is an estimated error.

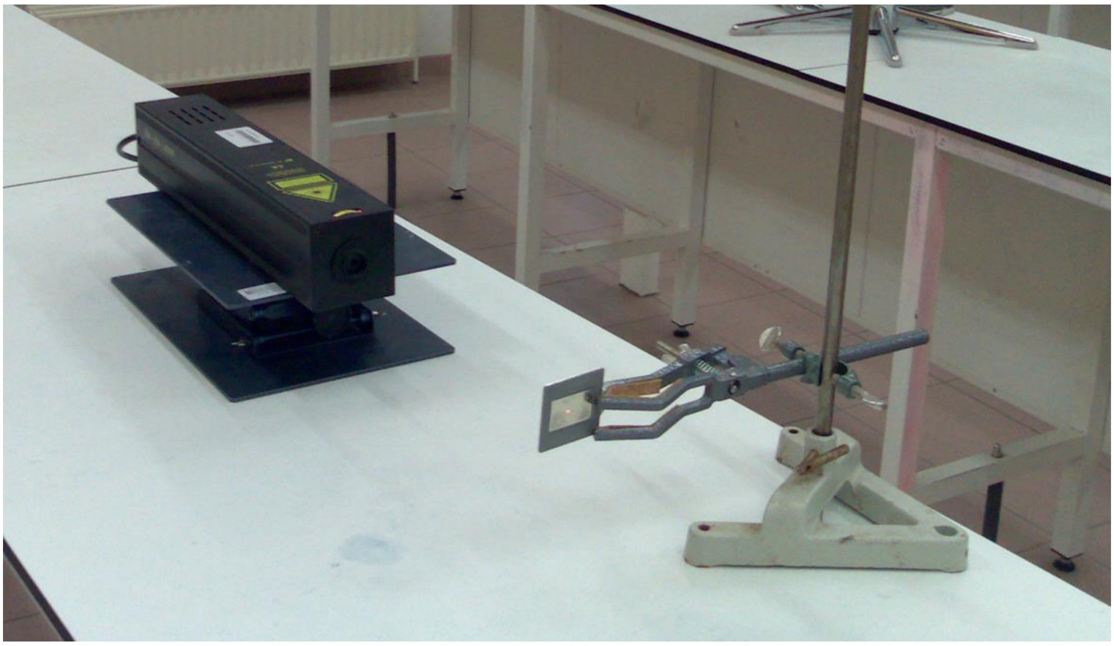

Figure 3. The LASER together with the double slit

4. Results and calculations

The goal of the experiment is: a) the qualitative presentation of the results of the Young experiment and b) the corroboration of the corresponding formula, which we will first derive.

Suppose that light, from a monochromatic source comes to a double slit, as shown in figure 4. We denote by a the spacing between the two slits, D is the distance between the double slit plane and the screen. The two slits are denoted by L, S respectively. The line MO is perpendicular to a at the midlepoint M and to the screen at the point O. OP is the distance of the constructive interference fringe of order k, which we denote by x. We draw two lines LP_1 and SP_2 normal to the screen.

Obviously from the two right angled triangles LPP_1 and SPP_2 using Pythagoras's theorem we have the following relations:

$$(SP)^2 = D^2 + \left(x + \frac{a}{2}\right)^2 \qquad (1)$$

And:

$$(LP)^2 = D^2 + \left(x - \frac{a}{2}\right)^2 \qquad 2)$$

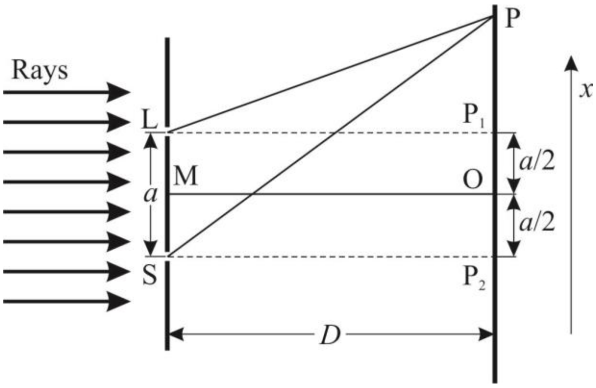

Figure 4. Schematic diagram used in the Young formula demonstration

Subtracting (2) from (1) and performing trivial calculation we get:

$$\left[(SP)-(LP)\right]\left[(SP)+(LP)\right]=2xa \qquad (3)$$

The second term in brackets, in the first member of the equation, is about 2D as $D \gg a$, and the distance x of any of the fringes is very small compared to D. So without any significant error we may set:

$$(SP)+(LP)\cong 2D \qquad (4)$$

It is well known that when light comes from coherent sources a point like P is a constructive interference point of order k if the path difference is k times the wavelength λ. So it must be:

$$(SP)-(LP)=k\cdot\lambda \qquad (5)$$

Substituting (4) and (5) into equation (3) we get the well known Young formula:

$$\lambda=\frac{a\cdot x}{k\cdot D}$$

where, to avoid any confusion, λ is the wavelength of the light, a is the distance between the two slits, x is the distance of the luminous fringe of order k from the central one, and finally D is the distance between the double slit plane and the screen (actually the wall). It is obvious that the measured quantity is x.

With regard to the results, we concentrated on the fringes near the central luminous fringe. We observed 4 luminous fringes at each side of the central one (figure 4). Thus the total number of luminous fringes was 9. The distance between the two edge fringes (right and left side) was $(24{,}0 \pm 0{,}2)$ mm. This error is also an estimated error.

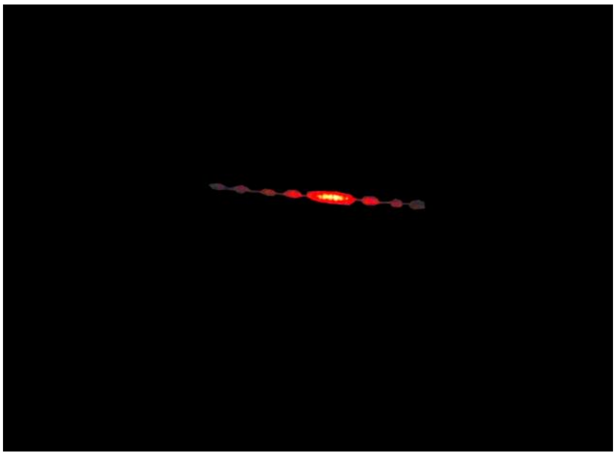

Figure 5. The observed luminous fringes on the wall.

The width of all 9 luminous fringes seemed to be the same, as well as the width of the dark fringes between them. The width of the dark fringes, which is easier to measure, was found to be the same for all of them, as $(1{,}0 \pm 0{,}2)$ mm. To find the distance, according to our measurements, between the central luminous fringe and one luminous fringe of higher order, we took into account that the measured total width of the eight dark fringes was $(8{,}0 \pm 0{,}2)$ mm, which means that the $(16{,}0 \pm 0{,}3)$ mm, until the total of $(24{,}0 \pm 0{,}2)$ mm measured, corresponds to the total width of the luminous fringes. As the width of all luminous fringes seemed to be the same (no better measurement was possible), we concluded, dividing by 9 (which is the total number of luminous fringes), that the width of each luminous fringe is 1,8 mm.

Thus to do our control on the reliability of the performed experiment, we should calculate the distances x of the different order fringes and compare them with the experimental values.

As already mentioned, the LASER wavelength and the slit distance are known and considered as error free – values provided by the factory.

In the first table below (TABLE 1) the experimental results are presented together with the theoretical calculations and the corresponding errors. The errors presented in this table result from the measurement precision and the theory of error calculation.

Table 1 Distance x [mm] until fourth order

k	Theoretical results	Experimental results
1	2.64±0,02	2.8±0.2
2	5.28±0.05	5.6±0.3
3	7.93±0.07	8’4±0.4
4	10.57±0.10	11.1±0.4

Comparing the calculated, (according to the theory) and the experimental results, we see that the theoretical results are in the range of the experimental values; we can therefore consider the experiment as being of good reliability.

5. Student’s presentation

We think that our conclusions would be incomplete if we did not include comment on the experience we have had, until now, of teaching Young’s experiment in class and explaining how this publication can help achieve better teaching in class.

It is obvious that in the classroom the overall problem that has to be solved is that students should, in the end, come to an understanding of light as a wave through the results of Young’s experiment. In our practical experience we have seen that without the historical presentation students did not understand why this experiment is so important and how it, in fact, contributed to a deeper understanding of light as a wave.

With respect to the experiment itself and the corresponding explanation of the calculations and the approximations used we did not have a major problem. As the source is practically monochromatic (He-Ne LASER), and the two slits very close (values already given above) the students did not have any problem understanding the calculations nor the approximations used because they observed how much bigger the distance LASER – screen was compared to the distance of the two slits between them.

When they try to measure the distance of the light fringes from the central one, and also measure the distance of the LASER from the screen, they begin to understand that this is not a trivial task, but requires a series of measurements which should be done with caution and repeated several times. At this moment it is a good idea to reintroduce the notion of the mean value of several measurements.

In the secondary program, in most cases, no analytic theory of experimental errors is included; in the presentation which was dedicated to the students we made only qualitative considerations concerning the experimental errors.

We should thus present the results as they are in table 2:

Table 2. Distance x [mm] until fourth order

k	Theoretical results	Experimental results
1	2.6	2.8±0.2
2	5.3	5.6±0.3
3	7.9	8.4±0.4
4	10.6	11.1±0.4

This means that the students should become, once again, aware of the fact that experimental error always exists and they should be invited to think where experimental errors come from in the specific case of Young's double slit experiment.

The next point, which is of major importance, is to make students think why Young's experiment is of such importance in Physics and thus one of the experiments very often included in secondary physics courses (This is in fact already explained in our introduction above). Students should understand that it was a simple experiment which proved the wave nature of light, giving at the same time the possibility of simple calculations which ensure that theory is describing reality accurately. To this end, we can make them calculate with measured distances from the central fringe, the LASER wavelength. Using the above mentioned values we find: $\lambda = 670$ nm. This has a relative difference of about 6% compared to the value given by the manufacturer. Thus the students understand that this method can also give quantitave results.

6. Students reaction and comprehension

The main goals of the Young experiment that we repeated in class are: i) students should get aware of the fact that light is a wave, that is that the experimental facts at the period that Young's experiment was performed were in favor of the wave nature of light, ii) students should also understand the analysis of the experimental procedure in detail, the calculations involved to obtain the results and the approximations and how these approximations can be justified, iii) the historical context, that is presentation in a more detailed way of the theories that existed at Young's time and why his experiment played a decisive role in favor of the wave nature of light (this point completes point (i) above).

To substantiate, by using a group of questions, the percentage of our goals which were achieved, we prepared a questionnaire. This questionnaire is as follows:

1. Did this experiment help you to understand why light presents the characteristics of a wave?
   a. Very much, b. Enough, c. A little, d. Not at all.
2. Did you understand the historical context and the controversy about light's nature at that time?
   a. Very much, b. Enough, c. A little, d. Not at all.
3. Did you understand the calculations that we used
   a. Very much, b. Enough, c. A little, d. Not at all
4. When performing the experiment we used a monochromatic (LASER) beam. Did you understand the difference with the procedure used by Young?
   a. Very much, b. Enough, c. A little, d. Not at all.

5. In your opinion which is the most important approximation that we used in our calculations?
6. Which are in your opinion the most important sources of errors in this experiment?
7. Why did we refer to Huygens's principle while discussing this experiment?

Taking into account the students responses to the questions we concluded that: A percentage close to 85% of the students understood very well, or well enough, the wave nature of light, whilst about 60% had a good understanding of the historical context and the controversies concerning the nature of light at that time. It is remarkable that only a few of them came to a complete understanding (11%) of the difference between the experiment performed by Young himself and the one we did in class using a LASER beam of practically one wavelength.

The students also had difficulties in understanding the main approximations used, the origins of experimental errors, and why we referred to the Huygens principle in our explanations.

In order to compare the results and deepen our understanding on students difficulties, we used the same questionnaire to another group of students this year (2013). Taking into account the students responses we concluded that: A percentage of 93% of the students understood very well, or well enough, the wave nature of light, whilst almost 70% understood the historical context and the controversies concerning the nature of light, at that time. It is remarkable that in this second group almost 70% of the students understood completely or well enough the difference between the class experiment and the one performed by Young himself.

In this second group the difficulties in understanding the main approximations used, the origins of the experimental errors, and why we referred to the Huygens principle, are restricted to only about 25% of the students.

If we compare the results obtained by the two groups of students, it is clear that the second group understood better all the points that constitute our goals. This fact is worth of an analysis of the reasons that led to a better performance the second group.

We presented first a brief presentation of the corpuscle theory of Newton and Grimaldi's point of view that light should be a wave. We did not "solve" at that moment the controversy between the two theories, we proceeded instead to the experiment which we presented with all the necessary details, concerning the experimental procedure itself as well as calculations and approximations used.

Only after this presentation we explained why Young's experiment leads to the conclusion that light is a wave and thus solve the controversy in favor of the wave theory.

It seems that the results obtained this way are much better than the previous ones and thus the procedure to be used is the one just described. Of course other teachers that might use our work as a guideline should check carefully the steps to be used and confirm or modify the described procedure.

7. Conclusions

If wave optics is included within the school syllabus, this experiment is among the most important. The goal of this experiment (and the analysis made of the results) is to make the students understand that the experiment (the one of Young in this case), gave clear evidence that light is a wave within a given historical context.

A deeper understanding of present day knowledge will come later on, perhaps in a University course, when the students find out that a similar double slit experiment reveals a wave nature for electrons. If they already know and understand Young's experiment they will find it easier to understand how this question of the duality wave-corpuscle is resolved through the statistical nature of the probability of finding a massive or non massive particle at a given point of space and at given moment of time.

Although the issue of the wave nature of material particles is rather a matter of a university course, a first contact with this subject can be achieved in secondary education. This can be done by experiment, if the necessary equipment exists, or by a computer simulation that exists on several internet sites which can be used to make clear that a wavelike pattern can also be obtained with material particles, such as electrons. Through combined simulations we also have the possibility of comparing the two cases [12, 13].

One of the most difficult points for the students turns out to be the historical significance of this experiment. Therefore the class teacher has to make clear that once the general rules of constructive wave interference are applied in this case, (they should obviously have already been taught in class), we find results that approach, to a very high accuracy , the observed data. This means that in the beginning we just suppose that light is constituted by waves and then we get results that justify this initial hypothesis.

One last but very important point is to explain, perhaps briefly but in a clear way, how Young managed to do such an experiment with the poor means that he had at that time. Our introduction above can guide the class teacher on that, but it is obvious from the results of our questionnaire that any subject teacher has to explain, as rigorously as possible, the monochromatic nature of the beam used in today's classroom. This description should not be dealt with first. It is more instructive to present how Young managed to do his experiment once the experiment with the LASER is already done and rigorously explained in class.

As already mentioned, the controversy of wave-corpuscle is one which dominated in the past. Nowadays it still very important, especially for people that are not engaged with natural sciences, and especially physics, as it may be their only contact with this matter.

For all students, even those following human sciences, the methodological approach to Physics problems, as expostulated above, is of great importance, as is an understanding of the pioneers of science and today's researchers. Given this, we should spend more time in class and find better approaches for the presentation of approximations and experimental errors. A first try is the one we made with the second group where we managed to achieve better results. This effort should continue by other professors. If the reader wants to do some further reading and research for himself, he is invited to use also some further bibliography [14].

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