Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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Using two models in optics

Students' difficulties and suggestions for teaching

Abstract

This paper focuses on difficulties linked to situations in Physics involving two models: geometrical optics and wave optics. The starting point is an investigation of university level students' difficulties in respect of this. Excerpts from textbooks are given to illustrate potential difficulties. A content analysis is then presented, underlining two main features which are required for dealing with such situations: awareness about the status of the drawings and « backward selection » of paths of light. Our argument is that these features could constitute some guidelines for the designing of innovative teaching strategies.

Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
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Introduction

This paper concerns the difficulties involved in the analysis, at university level, of situations which involve both geometrical and wave optics. As will be shown below, it seems that students have great difficulty in connecting these models of optics.

In the field of research on science education, few published papers are available, concerning this connection between models.

Several studies have shown[1] that when using the light ray model in teaching, in analysing shadows or image formation, many difficulties are likely to crop up. Wave optics are not dealt with in these papers.

Some authors[2] stress the lack of connection between geometrical and wave optics but do not develop this point of view any further.

Others[3] aim at building coherent bridges between these two fields of optics. Proposals for interpreting situations of geometrical optics (reflection and refraction at an interface) using the Huygens principle and observing these phenomena on a ripple tank are often made. This linkage between ray path and wavefront propagation is also used for image formation with a lens stressing the idea that within the framework of geometrical optics, a lens bends rays according to

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Descartes laws whereas in the framework of wave optics, it can be seen as a phase adjuster.

At the end of university courses, seeing image formation as a process of diffraction in the framework of Fourier optics is sometimes proposed[4]. In this research-study, we focused on an intermediary level of analysis which did not include Fourier optics.

Concerning what students understand about diffraction, Maurines[5] seems to denounce some of their responses which, as the analysis we present below shows, we find acceptable[6]. Such variants show the complexity of this field, and the lack of consensus on the way simple models, such as ray model of geometrical optics and diffracted waves, can be integrated in a coherent frame.

Other papers stress the deficiencies of students' understanding in the case of diffracting apertures[7], but do not particularly comment on the cases where a diffracting object and a lens are employed simultaneously.

As a contrast, we chose to analyse situations where diffraction and interference are observed in the presence of lenses, and we pay special attention to the meaning that the students ascribe to the « rays » traced on their diagrams.

In order to analyse students' difficulties in this complex case, we took into account the highly academic character of this topic, and we chose to work on very

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2 Place Jussieu
75251 Paris Cedex 05 France
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classic and relatively simple situations that are currently proposed in traditional teaching situations.

In our investigation, conducted at 3rd year university level, the students are faced with the same elements in each situation : an illuminated object, a lens and a screen on which a pattern is observed (fig.1).

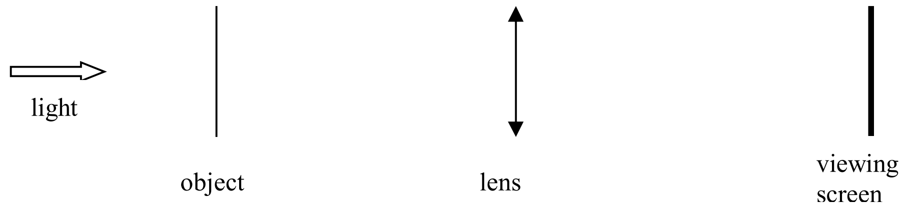

Fig.1. A prototypical situation in optics

At this level, students can use and need two models in order to understand all the variants of the prototypical situation : the ray model of geometrical optics and the wave model (a simple scalar theory is sufficient). These two models suffice to interpret what can be seen on a screen located somewhere beyond the lens. In some cases, the model of geometrical optics is sufficient. In other cases, the two models must be used together.

In the first part of this paper, we present our investigation of university level students' difficulties, in this respect[8]. These difficulties are presented along with excerpts from textbooks that are likely to produce obstacles to the proper understanding of the subject.

A content analysis is then presented, underlining two main features required to deal with such situations: awareness about the status of the drawings and understanding of « backward selection » of paths of light, a notion we will explain below.

Finally the argument is that these features could constitute guidelines for the designing of innovative teaching strategies, provided that the results of an investigation on teacher acceptance be favorable.

Students' difficulties

The investigation is based on students' responses to three questionnaires on the same prototypical situation, comprising an illuminated object, a lens and a screen (fig. 1). The location of the screen changes from one situation to another. Questionnaires 1 and 2 constitute the first questions of two different examinations on waves for students in the third year Physics at Paris 7 University. Questionnaire 3 is based on a very classic experiment previously studied during labwork. Students are given about 15 minutes to answer this test anonymously.

Here below, for each questionnaire, the questions are briefly outlined, correct answers are given and the main features of students' answers are reported. In this

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analysis, we call « image » the point-to-point replica, when it exists, of the object[9]. In such a correspondence, an object point and its image can each be seen as the source of a spherical or plane wave.

Questionnaire 1 : diffraction pattern of an object observed at the focal plane of a lens

This questionnaire concerns an absolutely classic situation, i.e. a plane wave which is diffracted by three holes punched in a screen (Situation 1). Such an object is very simple, because each hole is considered as a point source. The far-field diffraction pattern of the three holes is said to be observed on a screen located at the back focal plane of the lens (fig. 2).

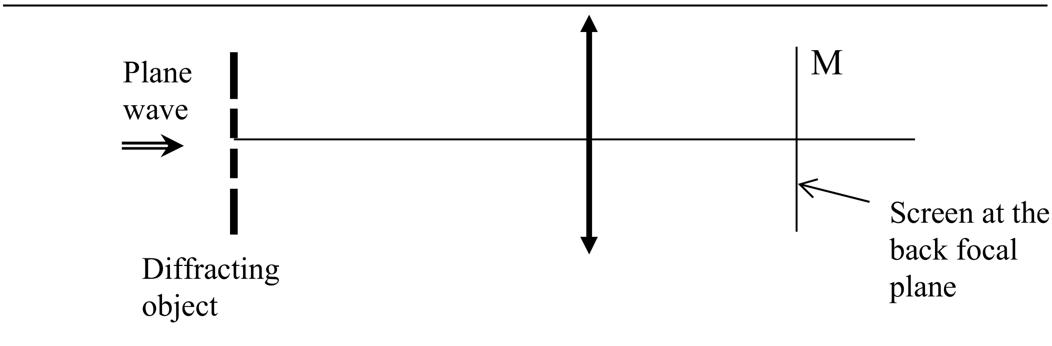

Fig. 2. Situation 1 : far-field diffraction observed at the focal plane of a lens

Students are asked,

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- in Question 1, to draw the paths of light coming from the holes and reaching a point M on the screen, to explain their answers and to mention the phenomenon which explains that light can follow these paths ;

- in Question 2, to calculate the amplitude of the field at M and to justify their calculation.

A correct drawing is given in figure 3.

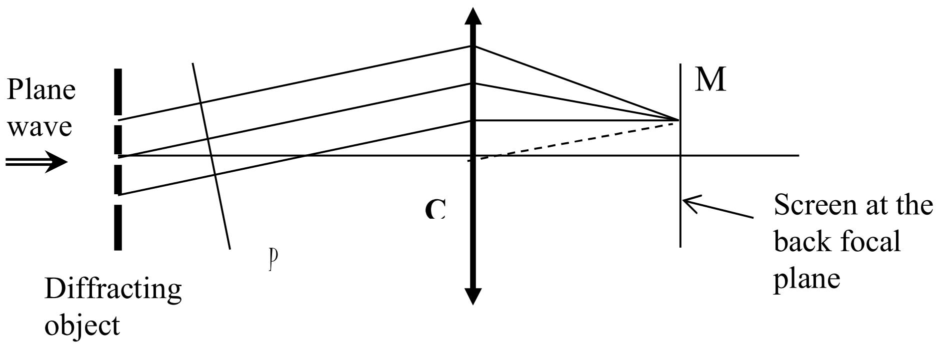

Fig. 3 Paths of light reaching a point (M) of the back focal plane of a lens in Situation 1

Because three coherent spherical waves overlap on the screen, Situation 1 cannot be analysed with geometrical optics only. Nevertheless, the path of each separate constituent wave coming from the diffracting screen and reaching M is based on geometrical rules. The three paths are parallel to the direction CM where C is the optical center of the lens (fig. 3). Of course, students should mention diffraction to justify the relevance of these paths, which cannot be predicted in the frame of geometrical optics alone.

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A calculation of the phase differences between the three waves at point M is needed according to the principle of superposition. These differences are proportional to differences in optical path length which can easily be determined using « geometrical » properties of the lens, knowing that the optical path lengths between a plane (($\mathcal{P}$) on fig. 3) situated before the lens, perpendicular to the considered paths and the corresponding point (M) on the screen are equal.[10]

From students' justifications, this situation is expected to show whether or not it is mistaken for the classic situation of geometrical optics (figure 4) where a sole plane wave is transformed by the lens into a spherical wave converging on a point M of the back focal plane of the lens.

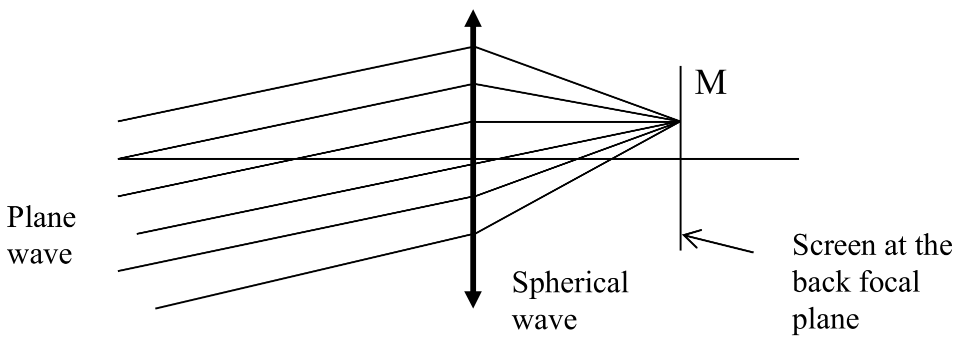

Fig. 4. A situation of geometrical optics (not to be mistaken for Situation 1) : a lens transforms an incident plane wave into a spherical one.

Therefore, what is at stake in these questions is not so much the ability to find the correct result of a calculation but rather to see what the students' reading

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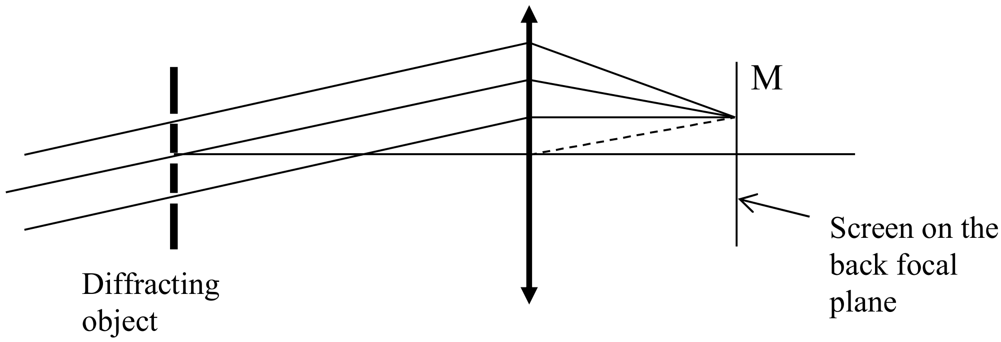
of this type of situation is and, especially, what status they ascribe to the paths of light they commonly draw.

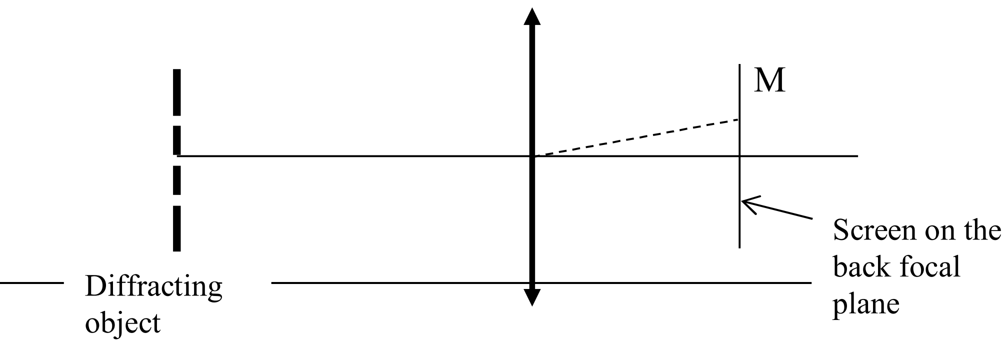
The results confirmed that, although very basic at this level, students found these questions far from obvious.

In Question 1, only half the students (N_T=250) gave correct drawings and justifications. Rather surprisingly, nearly a third of the students (28%) did not mention the phenomenon of diffraction at all. Some typical answers (14%,) are given on figures 5a et 5b.



The screen is on the focal plane of the lens. So, point M is the image of an object coming from infinity.

Fig. 5a: Diffraction at infinity: an answer which suggests that there is an optical image on the screen.



The rays arriving on the holes are parallel. As they pass through the holes, these rays are deviated but remain parallel.

Fig. 5b: Diffraction at infinity: an answer which suggests that there the holes simply deviate the rays.

It is worth noting that in both Fig. 5a and 5b the drawings between the holes and the screen are correct and that it is the students' reading of these drawings which is erroneous. Therefore, the problematic feature seems to be strongly connected with the status of paths of light.

These students seem to forget or misunderstand the phenomenon of diffraction and so consider the lines they have drawn as rays of geometrical optics that go straight on through the holes to an image on the screen (fig. 5a) or that are « deviated » by the holes as refracted rays at the interface of two media (fig. 5b). In both cases, it seems as if a given line represented the same entity before and beyond a hole. This apparent continuity of the « rays » is suggested by the fact that only the paths of light reaching point M are drawn, thus excluding the multiplicity of paths of light that can be envisaged at the exit of each hole. Moreover, this impression of continuity could be reinforced by the similarity of the symbols commonly used along the entire paths of light[11].

In Question 2, correct calculations of the amplitude of the field at a point on the screen are very frequent (80%), but as repeatedly pinpointed by many authors[12], this is not enough to evaluate the extent of students' understanding of the situation. Most of the students do not justify the calculation of phase differences. Typical justification is that given in the following comment:

The lens transforms the plane wave into a spherical wave. Following the Malus theorem, plane $\mathcal{P}$ (figure 3) *is a wavefront.*

In this case, students grouped the paths of light and they thought of these paths as representing a sole wave (plane before the lens, spherical between the lens and the screen). What is forgotten is not only the diffraction of the incident plane wave by the holes but also the superposition of the three spherical waves at point M. This superposition does not allow one to use the sole model of geometrical optics to interpret the situation between the holes and the screen of observation. A reinterpretation of the Malus theorem is needed, keeping to the equality between optical paths, but leaving aside the idea that the drawn parallel lines are associated to a unique plane wave.

Many authors of textbooks do not seem to be aware of these difficulties[13].

For instance, figure 6 shows a diagram with its corresponding caption[14], which mentions a plane wave and is therefore not compatible with the idea of difference between the phases of the waves superimposed at point M.

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75251 Paris Cedex 05 France
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*The wavefronts associated with the diffracted rays are planes perpendicular to their given direction **u**, (...) where **k** is the propagation vector of the plane diffracted wave.*

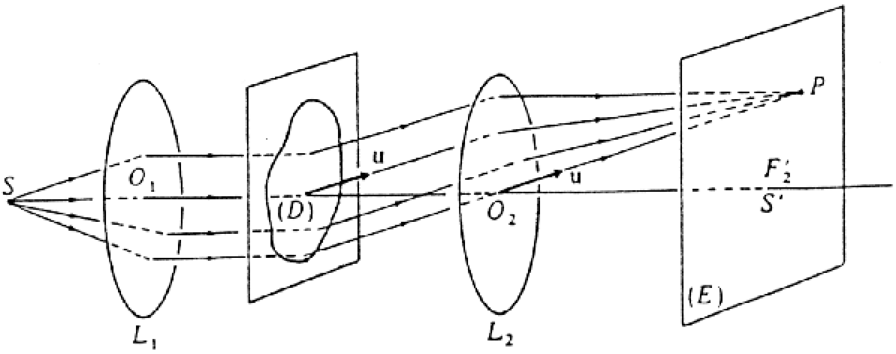

Fig. 6. Diffraction of a plane wave by an aperture: a document with a problematic caption.

This kind of presentation could mislead the students. Indeed, there is no suggestion of diffraction except the change in direction of the « rays ». Each ray representing the incident plane wave on the diagram, arriving on the aperture has one and only one extension beyond the aperture. As explained above, this continuity is reinforced by the way it is symbolized, as the same arrow is put on the lines drawn from the source (S) up to the point (P) of the screen. Moreover, the caption mentions plane « wave fronts » which are perpendicular to a « diffracted rays » and also « plane diffracted wave ». So, the students have every reason to consider this grouping of paths of light beyond the aperture as a sole plane wave, diffraction and superposition being rubbed out.

Such results, we think, strongly reinforce the potential interest of stressing the fact that what confers their status to particular rays is the grouping which appears relevant in a particular problem. We will come back to this idea of grouping of paths of light below.

Questionnaire 2 : a diffracting object and its image on the conjugate plane of a lens

Questionnaire 2, like Questionnaire 1, constituted the first question of an exam on waves. Except for the items of this questionnaire, the whole exam is about far-field diffraction observed at the back focal plane of a lens. The analysis is based on the answers given by 169 students (3rd year Physics, University Paris 7).

Questionnaire 2 concerns a very classic situation, i.e. a slide which is illuminated by a plane wave and its image, observed on a screen located on the conjugate plane of this slide with respect to a lens (Situation 2, fig. 6).

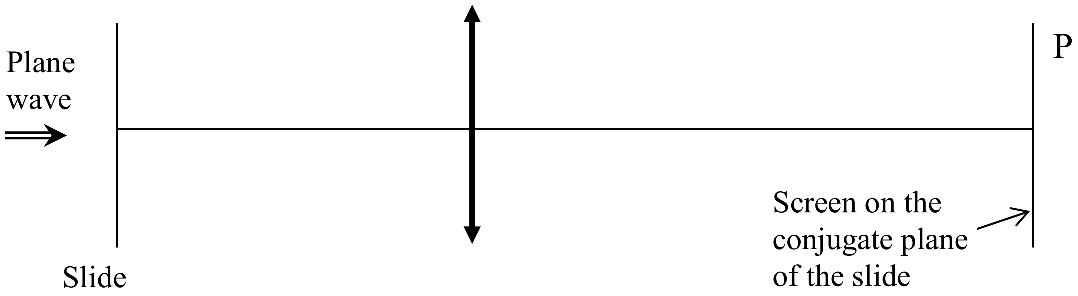

Fig. 6. Situation 2: image formation with a lens

Students are asked to draw at least three rays coming from the slide and converging towards a point (P) on the screen, out of the optical axis. No aberration and diffraction effects by the lens are said to be taken into account between the two given conjugate planes, the slide and the screen.

An accepted answer, in the framework of geometrical optics, is based on the stigmatism of the lens. The image is a point-to-point replica of the object and all the rays diverging from one point on the slide and reaching the lens are considered to converge towards the same - image - point. To find the location of the conjugate object point of point P, a particular ray whose trajectory is well-known ("central" ray or "parallel" ray in fig. 7) can be drawn, then all the rays reaching point P can be easily found.

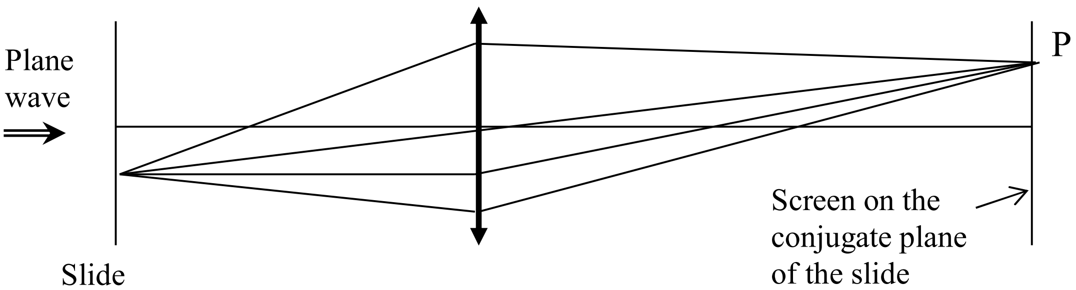

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Fig. 7. Point-to-point correspondence of geometrical optics between two conjugate planes

For such a basic question of geometrical optics, only 27% correct answers were found. More than half the students (54%) did not respect the point-to-point correspondence between an object and its image (see figure 8a, 8b et 8c).

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75251 Paris Cedex 05 France
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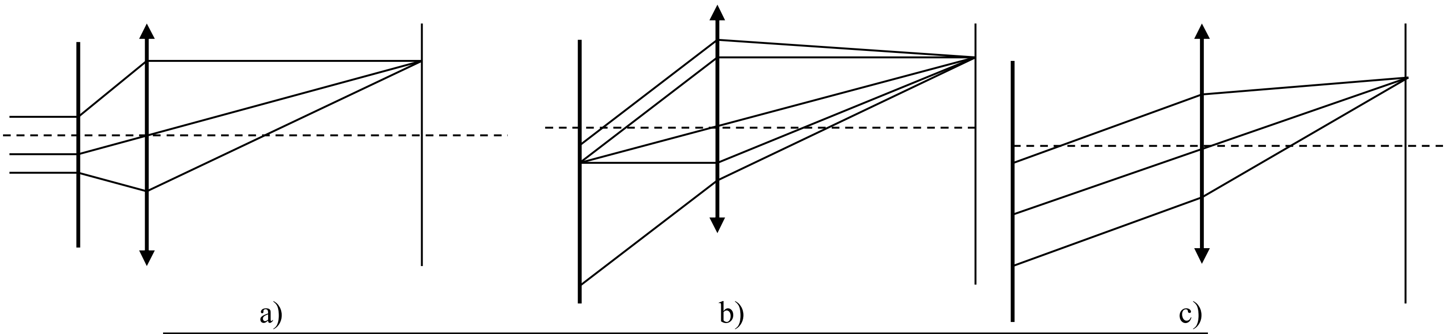

Fig. 8. Some answers to questionnaire 2, that do not respect the point-to-point correspondence between an object and its image.

It seems that, once again, students are not aware of the meaning of their diagrams, which often suggest at a point on the screen, superposition of waves emitted from different points on the slide. Students' answers show that the very special grouping of paths of light of « geometrical » imaging does not seem to be too obvious to them. The idea of diffraction which is the main topic in this test, interferes with the « geometrical » analysis.

Questionnaire 3 : Enlarging fringes of interference with a lens

This questionnaire, put to 120 university level Physics students (2nd and 3rd year), concerns an experiment (Situation 3) which is very classic at this level. When fringes of interference need to be enlarged for a better observation or to allow measurements, a converging lens is used with a screen behind, at a good distance.

In Questionnaire 3, a Young's experiment is shown as in schema 2 (figure 9)

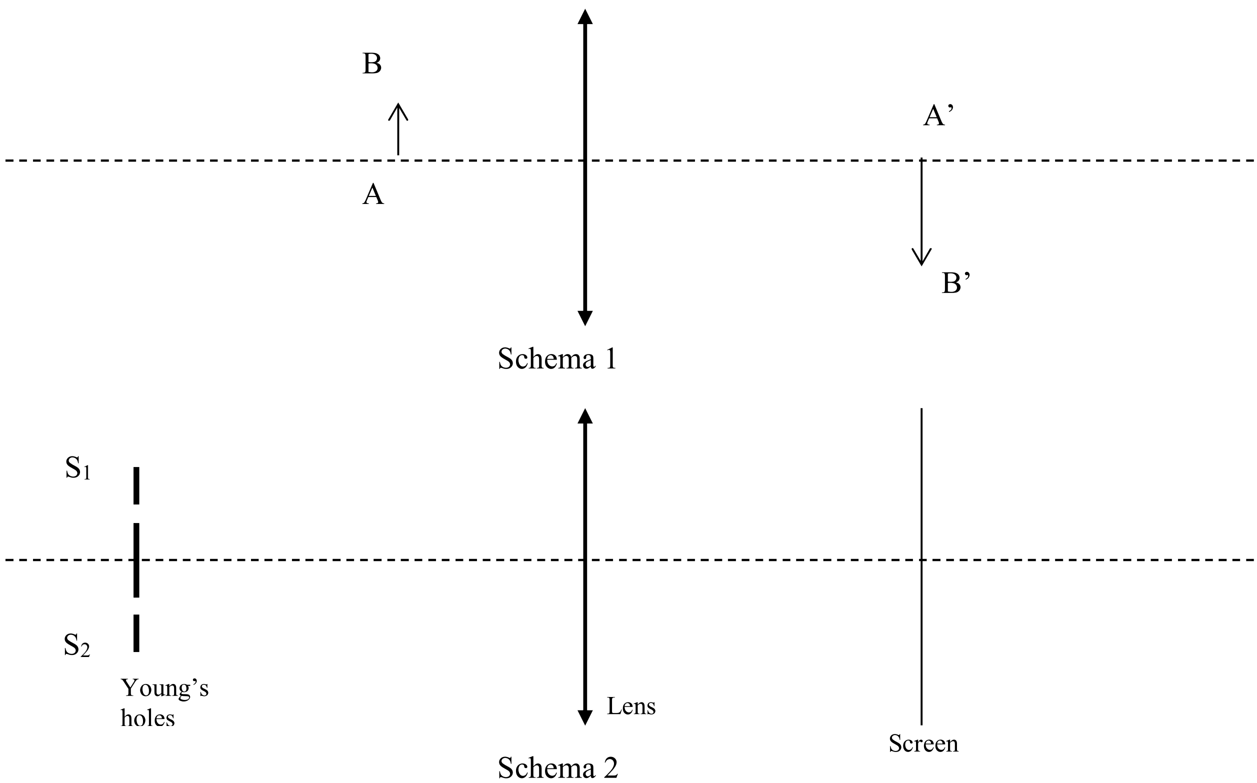

Fig. 9. Situation 3: Enlarging fringes of interference with a lens.

Once again, there is an illuminated and diffracting object (the two Young's holes), a lens and a screen. But, this time, the screen is located neither on the focal plane of the lens, nor on the conjugate plane of the holes.

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LDSP, Université Paris 7 - Denis Diderot, Case 7086
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The kind of question is quite unusual. It deals, directly this time, with the status of what is observed on the screen : are the finges observed on the screen the image of something produced by the lens?

A diagram (schema 1, figure 9) shows the location of an object whose image could be observed using the same lens and keeping the screen at the same place. This provides the students with the couple of conjugate positions (with respect to the lens) that are directly relevant to this question.

In fact, the correct answer is not straightforward.

An answer commonly considered as correct by teachers states that the pattern on the screen is the image given by the lens of the fringes which can be seen on the conjugate plane of the screen. The optical correspondence of geometrical optics is directly used without any question about the status of the « object » constituted by the fringes. This point, we think, should be reconsidered.

It is true that some fringes of interference can be observed on the screen, but, according to us, these are not the image of the fringes located on the conjugate plane of the screen. Indeed, the paths of light which are followed by each wave emitted by a hole and reaching a point (M') on the screen can be drawn (fig. 10). To find these paths, we rely on the properties of the lens, e.g. on rules of geometrical optics.

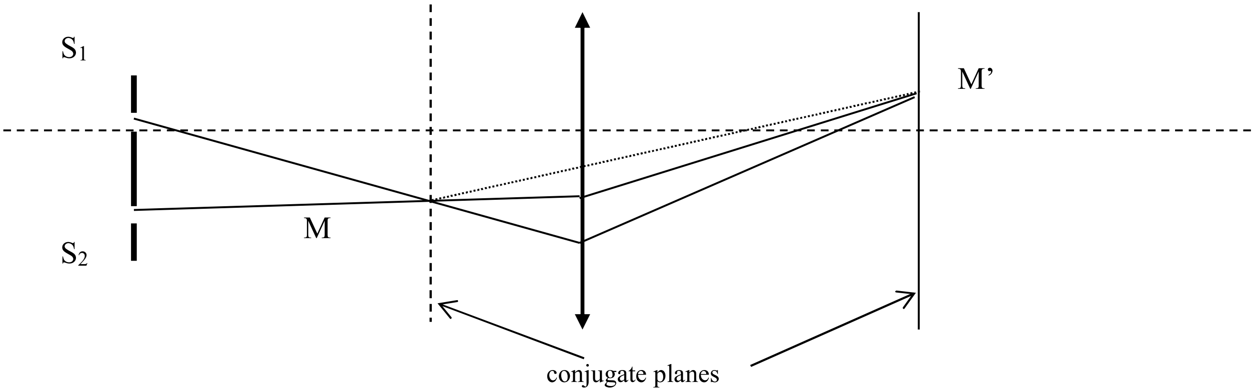

Fig. 10. Paths of light reaching a point of the screen in Situation 3.

Looking at figure 10, it should be stressed that, within the frame of this analysis, there are only two paths leading from sources S_1 and S_2 to point M' on the screen, one for each component wave. So, point M cannot be considered as the point source of a spherical wave[15] the path of which could be analysed in isolation as in geometrical optics. In the following section, we will describe some critical experiments which illustrate the value of such a viewpoint.

In the currently accepted answer, the two models are used successively. First, the wave model is used to interpret the fringes produced by the Young's holes on the conjugate plane of the screen of observation. Then, these fringes are considered to be enlarged by the lens according to classic rules of geometrical optics. Such a kind of reasoning is also illustrated by the excerpt of textbook[16] on figure 11 which concerns the enlargement of a diffraction pattern.

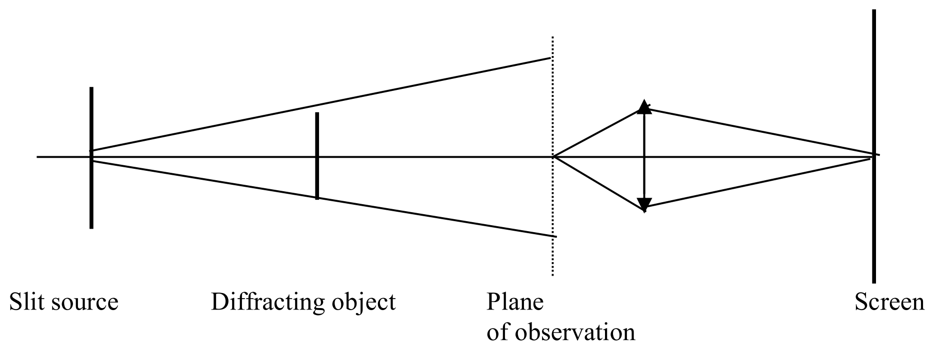

Figure 11 Enlarging a diffraction pattern : a problematic document

In fact, in order to avoid dividing the situation into two separate parts, and to keep the coherence of reasoning, global interpretation is necessary. According to us, the presence of the lens should not be seen as changing anything in the principle of Young's experiment: two waves are still overlapping on the screen. The lens only changes the path of each component wave, in a way that follows the rules of geometrical optics (fig. 10), and the observed pattern is still to be interpreted in the frame of wave optics, since it is obtained by the superposition of two coherent waves. Thus, the two models, ray model of geometrical optics and

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LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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wave model, are needed to interpret the situation and to conclude that the phase difference is the same at points M and M'.

Not surprisingly, no complete answer implying the two models was proposed by the students (N_T=120). Even if the drawing of the paths of light reaching a point on the screen (fig. 10) was not asked for in this questionnaire, according to us, the understanding of the situation is based on this drawing, which illustrates the selection of paths of light and the part of the lens. The absence of such a diagram in the students' answers shows that either the students were not able to produce it, or they did not find it useful for their answer.

Nearly a quarter of the students (24%) did not give any answer.

Nearly half (46%) used only one model to give an interpretation of the pattern observed on the screen. In case where this was the ray model of geometrical optics, the students tried to find the object having the fringes as the image. Sometimes, the holes S_1 and S_2 were supposed to be the object looked for. In case where the wave model was used, no further explanations were given concerning the fringes observed on the screen or the part of the lens. The presence of this lens was so problematic that some students considered that it could not be linked in any way with the fringes produced on the screen.

Finally, only a quarter of students (24%) used the two models but even then, only in a successive manner, as in figure 12.

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75251 Paris Cedex 05 France
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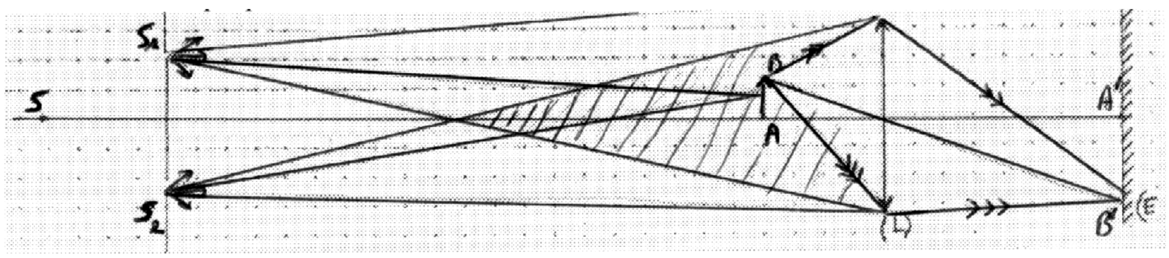

Fig. 12. A student's drawing showing a successive use of the two models in Situation 3.

The difference between the two parts of the diagram (fig. 12) is very striking. It conforms to the currently accepted answer and seems to be a far cry from a global understanding of the situation. In particular, no clues are to be found about the meaning of the paths of light and the status of point B on this diagram.

Recap on students' difficulties

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LDSP, Université Paris 7 - Denis Diderot, Case 7086
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75251 Paris Cedex 05 France
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Ours findings showed that, even in very classic situations with traditional questioning, many students were a long way from mastering the two models and their range of application.

Situation 1, which involves a diffraction pattern of an object observed on the focal plane of a lens, raised difficulties that could be linked with a story-like reading of the diagram. In the answers collected, diffraction and superposition seem widely neglected, and therefore nothing stands in the way of the well-known tendency to analyse physical situations as stories with a unique hero[17]. In many answers, students mentally seem to follow the " route " of a sole entity, a " ray " or a " plane wave ", from left to right, through the holes (fig.5). The narrative connotation[18] of the diagram might be reinforced by the fact that only parallel paths of light are represented beyond a diffracting object, thus suggesting a plane wave (fig. 3 and 6), and/or by the use of similar arrows in front of and beyond a hole on what appears, consequently, as a unique « ray » (fig.5).

Situation 2, i.e. image formation of a diffracting object by a lens, has shown that, even for this seemingly classic case, the very particular grouping of paths of light based on the stigmatism of the lens is not straightforward. In fact, many students showed a lack of awareness about the meaning of what they had drawn, as they seemed to justify that a point on the screen was an image point by considering

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some paths of light which converge on this point but come from different points of the diffracting object.

Situation 3 permitted us to pinpoint the fact that difficulties increase when the screen is not located on the focal plane of the lens or on the conjugate plane of the diffracting object. A quite unusual question, bearing on the status of the lighting of the screen, turned out to be most destabilizing for the students. To answer, they often seemed to rely on a rigid link between one element of a situation and the choice of a model, a lens being associated with geometrical optics, and an interference setup with wave optics. If this implicit rule, only one model for each case, was perceived as too restrictive, some students got round the difficulty by artificially dividing up the situation and using one model after the other (fig. 12). This goes with an unquestioned view on the crossing of two paths of light as the source of a classic spherical wave.

All these difficulties are strongly connected with the reading of the diagrams, a point which therefore deserves special attention in teaching. The overall question, i.e. explaining what changes are brought into an optical situation by only moving the screen, turned out to be rather thought provoking, and is likely to be very valuable in a perspective of conceptual understanding of models used in optics. If this goal is adopted, a key notion is that of the grouping of paths of light appropriate to each situation. This grouping changes even if the screen alone is

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75251 Paris Cedex 05 France
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moved. In brief, what is changed « downstream » must affect what is considered « upstream », and a simple story-like view of the physical situation has to be renounced.

These few remarks constitute the basis of our suggestions for teaching.

Suggestions for teaching : the content revisited

The results of this investigation led us to revisit the content of optics as taught between the end of secondary school and specialised courses at university, i.e. before Fourier Optics. We think that a major notion at these intermediate levels is that of « backward selection » of paths of light[19].

« Selection » must be stressed, we think, because students often forget that an infinity of paths of light are to be envisaged beyond a diffracting object, and that paths must be selected so as to interpret what is observed on the screen. The selected paths depend of course on the location of the point chosen on the screen and on the location of the screen itself. Having determined the arrival point, it is necessary to look « backwards » to know which paths to select and how this selection works.

This notion of backward selection is not explicitely used in textbooks[20]. Geometrical optics and image formation are first presented to students ; then, the wave model is used to interpret interference and diffraction. But, usually, students must wait for Fourier optics to see that for the same object, a lens can give a diffraction pattern or an image of this object according to the location of the screen.

To get a coherent and synthetic view, we suggest introducing the notion of backward selection very early on in the teaching process, be it in the sole frame of geometrical optics[21], and in any case without waiting for more sophisticated topics such as optical filtering or strioscopy. Selection of paths of light converging on a point on the screen and the grouping of rays could be emphasized as two related aspects, avoiding students reasoning on " isolated " paths as they often do.

At this stage, backward selection could be linked not only to the kinds of grouping but also to the status of paths of light. A line on a diagram, indeed, may represent two different things, a « path for (the calculation of) phase » if superposition is to be taken into account, or a « path for energy »[22] if only one wave is to be considered, the sole model of geometrical optics being then sufficient.

The questioning on the status of paths of light leads to another on the respective status of the intensity pattern on the screen and of the sources.

For the sake of brevity, all these points are illustrated hereafter using only one setup, two Young's holes and a lens, in order to show the variety of situations

Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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which could be proposed by changing only one parameter : the location of the screen. In this instance, the object is constituted of two point sources only.

Two holes and a lens : analysing different variants

Three situations involving the same object and lens, along with their analysis, are presented in this section, in the terms proposed above. In the third case, two complementing experiments are described.

Image of Young's holes

Given two Young's holes, the screen can be located at the conjugate plane of the holes. The images S'_1 and S'_2 of the two holes are then observed on the screen (fig. 13a).

Between the holes and the screen, a classic analysis in the frame of geometrical optics can be conducted, given that no superposition of different waves occurs on the screen. The spherical wave coming from S_1 (resp. S_2) converges at the image point S'_1 (resp. S'_2). The two considered waves are geometrically separated in S'_1 and S'_2. The paths of light selected by each image point can be considered as « paths for energy » between the conjugate planes. The lens plays its part as an imaging system.

Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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Fringes of interference observed on the focal plane of the lens

The screen is now located on the focal plane of the lens (fig. 13b). It is often this situation which introduces the phenomenon of interference in teaching, because calculating the difference in path length is very easy (see above Question 2 of Situation 1).

The first point to stress is that, among all the paths of light coming from the holes (fig. 13a) only two paths reach point M' of the screen. Secondly, these two paths are associated with different waves, one for the source S_1 and the other one for the source S_2. Thus, the selected path have completely changed when the screen is moved. The case here is that of superposition of waves at a given point. This time, the selected paths are only « paths for (a calculation of) phase » and no longer « paths (to be understood as routes) for energy ». The fringes cannot be considered as the image of something through the lens. The lens only determines how each spherical wave, supposedly alone, is propagating up to the screen, and this can be analysed easily by geometrical optics. Knowledge of the location of images S'_1 and S'_2 of the sources is worth pinpointing as it lets us determine the path of each wave to any point beyond the lens.

Enlarging fringes of interference

The screen is now located beyond the lens but neither on the back focal plane nor on the plane conjugate to the holes.

The analysis is of the same type as in the preceding situation (fig. 13b). The fringes observed on the screen are not, strictly speaking, the image of other fringes. It is true that the interference pattern on the screen is an enlargement of the fringes which would be seen on the conjugate plane of the screen by using for instance a tracing paper, but in the absence of such a paper, the phenomenon is different, even if the observed pattern is the same.

Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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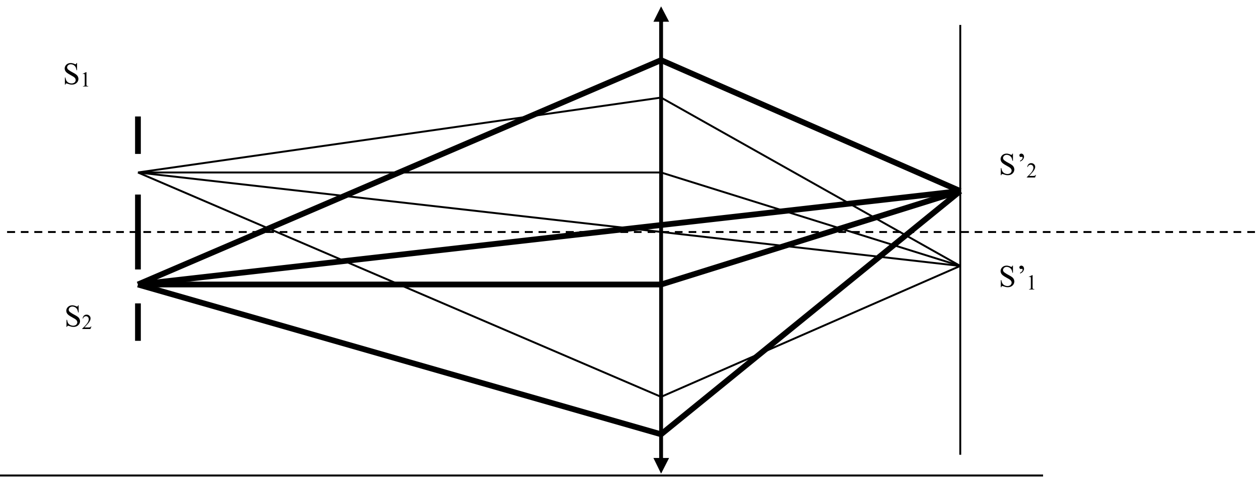


Fig. 13a. Image of the Young's holes with a lens.

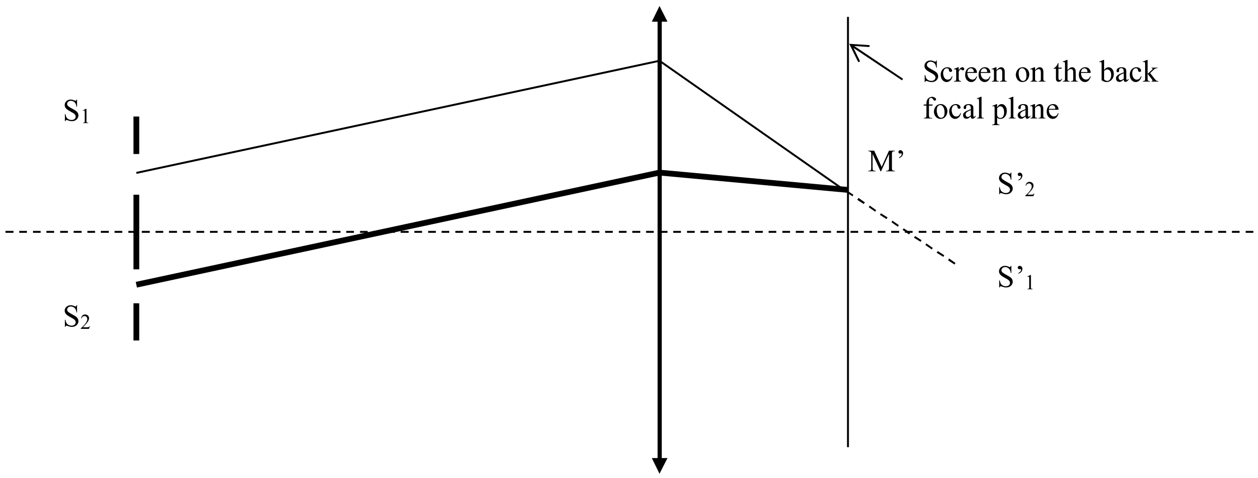
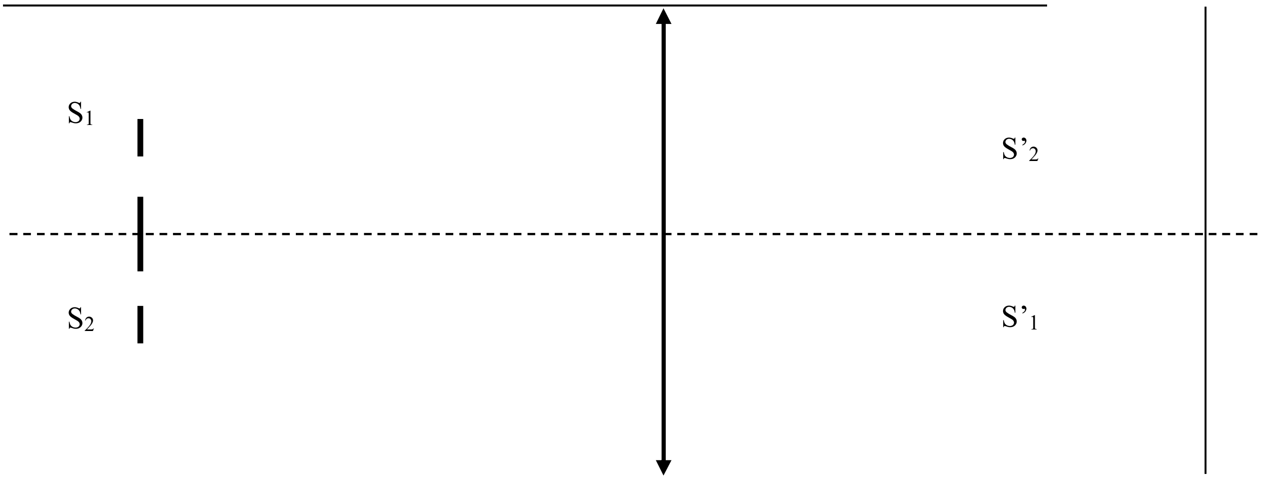


Fig. 13b. Fringes of interference observed on the focal plane of a lens.



Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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Fig. 13c. Enlarging fringes of interference : is there an image of fringes on the screen ?

Philippe COLIN, Laurence VIENNOT
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2 Place Jussieu
75251 Paris Cedex 05 France
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As an illustration that questioning about the status of what is seen on a screen is not pure speculation, we suggest two simple but unusual experiments which will show this.

In a first experiment, a mask covers a part of the lens (fig. 14). In many investigations about optical imaging[23], students are asked to predict what happens to an optical image in such a case, the correct answer being that only the luminosity of the image is affected. Instead of this, answers commonly found seem to stem from a holistic model, the image traveling as a whole, and arriving on the screen along with a black hole after having made contact with the mask.

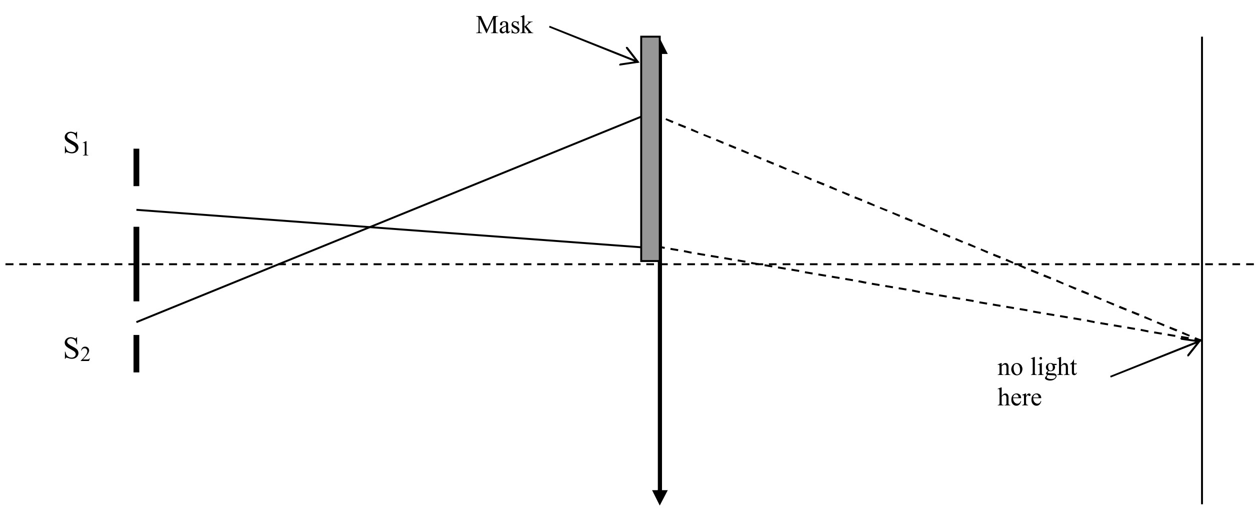

Fig.14. A critical experiment for the status of the observed fringes

Here, similarly, the students can be asked to predict and justify their prediction as to what will be observed on the screen. We have seen that many students seem to use the two models successively (see Questionnaire 3), thus dealing with the final part of the setup as with the transformation of a unique spherical wave by the lens. If no difference is made between Huygens sources and classic point sources of geometrical optics, answers may be given that the same fringes will be observed on the screen, but just a little dimmer, according to the size of the mask. This is not what is observed on the screen at all when the mask is on the lens : some fringes completely disappear and those remaining maintain their brightness. This surprising observation could foster the use of backward selection to interpret the lighting of the screen (fig. 15). Therefore it would be possible to show students the way to give correct meanings to paths of light, here only « paths for phase » and, finally, to link the status of the lighting of the screen to the status of the sources.

To illustrate this difference of status of sources, tracing paper can be placed on the conjugate plane of the screen (see fig. 15).

Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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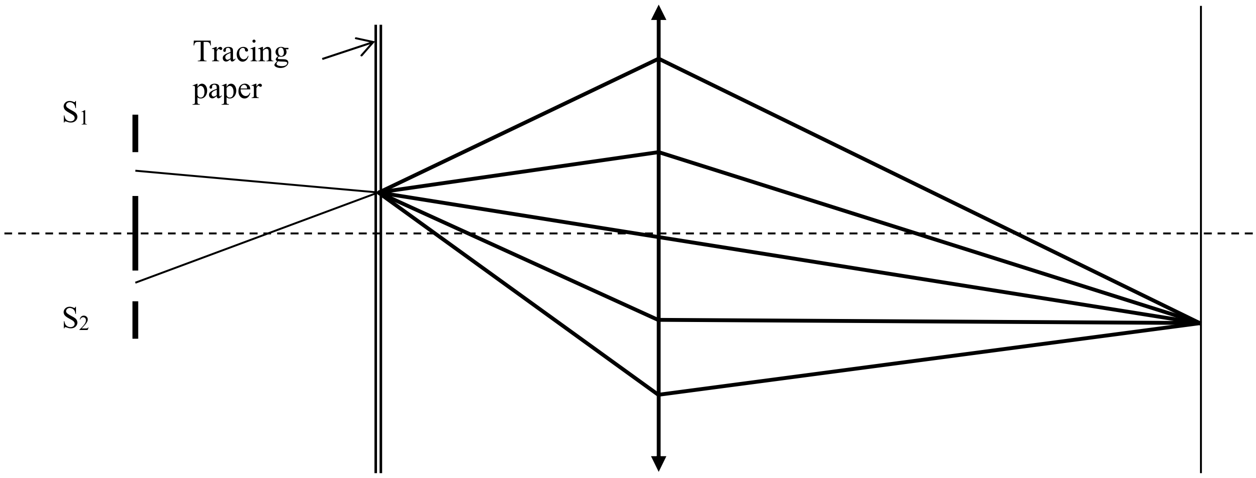

Fig. 15. A tracing paper is used to recover the " classic " sources of geometrical optics

When using the tracing paper, although the fringes observed on the screen have the same aspect as before, they can be considered as a classic image of geometrical optics : when a mask covers a part of the lens, a global decrease of image luminosity can be observed on the screen. But when the screen is moved, the tracing paper staying in place, no fringe can be observed because the tracing paper destroys the coherence of the sources S_1 and S_2 and consequently the overlapping waves do not produce any fringes of interference.

So, with these three situations several basic elements of optics : ray, source, object, image, come under discussion.

Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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Far from a strict partition of optics between geometrical and wave optics, backward selection goes along with a global approach, which focuses on the changes imposed on the understanding of the situation according to where the screen of observation is located.

Recap and concluding remarks

This piece of research was focused on students' understanding about the use of two models in optics, geometrical and wave optics, and, correlatively, about the status of the lines that they draw on their diagrams in order to analyse some classically taught situations.

The analysis of the three questionnaires the students answered showed that a lot of them had not mastered how to use the models of optics that were available to them at their academic level, e.g. Fourier optics excluded. The difficulties observed seem to be strongly connected with misreading the drawings classically used in optics, and are probably linked to a lack of awareness about the status of the drawn lines.

We suggest that the notion of a « backward selection » of paths of light would be a very useful guideline for teaching this. With such an approach, a situation is analysed by starting from the considered arrival point of light. Contrary

Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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to a story-like reading of the diagrams, this way of analysing situations in optics avoids the rigidity commonly observed in such a case, i.e. superficial reading of the diagrams and all the ensuing misunderstandings.

It then becomes possible to change the grouping of the considered paths of light according to the position of the screen, and, furthering this, to ascribe a different status to these lines according to their grouping. This linking of backward selection to the status of paths of light is quite a new approach because, in traditional teaching, this point is not fostered at all.

The next step could be to link the status of paths of light and the status of the lighting of the screen as well as the status of the sources. A way of presenting this problem in a more concrete manner is by doing experiments that use masks and tracing papers, while organising a debate with students about the expected phenomena and those actually observed, which are surprising even to teachers.

It should be kept in mind, however, that all this analysis is only valid in the absence of another diffracting element between the first diffracting object and the screen. Indeed, it is well known that the point-to-point correspondence between an object and its optical image is broken in such a case. A more complete didactic proposal remains to be elaborated in order to deal with such cases on the basis of a clear characterization of the status of Huygens Fresnel sources.

This being said, further questioning should take place before such views be proposed to teachers. Informal discussions clearly showed that, although it cannot be spoken of new Physics, some colleagues found this « revisitation » most disturbing. All too often, research-based didactic suggestions are not accepted, or if accepted are deeply transformed, because, to use a metaphor, there is no adaptation of impedance between the transmitters and the supposed receivers of the didactic message[24]. A further research study has been conducted by one of our team[25] in order to appreciate to what extent university teachers are likely to agree with our viewpoints and share our wish of introducing innovative strategies in this domain of our teaching. Ten university teachers were interviewed, each for more than two hours. Their opinions will be reported in a forthcoming paper, as well as several intricate formats of possible didactic sequences. These didactic structures, all founded on the ideas presented above, have been classified in order of decreasing teacher acceptability[26]. The main potential obstacles to the adoption of our proposal, as well as some useful facilitators, have been identified.

This second part of our study is oriented toward the implementation and assessment of an innovative sequence on this topic.

References and notes

Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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[1] See, for example, I. Galili, « Students' conceptual change in geometrical optics », International Journal of Science Education , **18** (7), 847-868 (1990) ; I. Galili and A. Hazan, « Learners' knowledge in optics : interpretation, structure and analysis », International Journal of Science Education, **22** (1), 57-88 (2000) ; F. Goldberg,. and L.C. McDermott, « An investigation of students' understanding of the real image formed by a converging lens or concave mirror », American Journal of Physics, **55** (2), 108-119 (1987) ; K. Wosilait, P. R.L. Heron, P.S. Shaffer, and L.C. McDermott, « Development and assessment of a researched-based tutorial on light and shadow », American Journal of Physics, **66** (10), 906-913 (1998).

[2] J. Dunin-Borkowski, « Crooked paths of straight rays », in *Proceedings of International Conference on Physics Education GIREP'93*, Minho University, Braga, Portugal, 16-21 July 1993, edited by L.C. Pereira, J.A. Ferreira, and H.A. Lopes, pp. 333-337.

[3]G. Verkerk, G. and R.E.A. Bouwens, « Learning optics from seeing light » in *Proceedings of International Conference on Physics Education GIREP'93*, Minho University, Braga, Portugal, 16-21 July 1993, edited by L.C. Pereira, J.A. Ferreira, and H.A. Lopes, pp. 100-121.

[4] C. Taylor, « Images, optics and education » in *Proceedings of International Conference on Physics Education GIREP'93*, Minho University, Braga, Portugal, 16-21 July 1993, edited by L.C. Pereira, J.A. Ferreira, and H.A. Lopes, pp. 122-136.

[5]L. Maurines, « Students and the wave-geometrical model of the propagation of waves in a three dimentional medium » (In *Research in Science Education in Europe* edited by M. Bandiera and al, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1999), pp. 103-112.

L. Maurines, « Spontaneous reasoning on light diffraction and coherent illumination optical imaging », in *Proceedings of the Second International Conference of the European Science Education Research Association* (ESERA), Research in Sience Education. Past, Present and Future, 31 August - 4 Sept. 1999, Kiel, Germany, edited by M. Komorek, H. Behrendt, H. Dahncke, R. Duit, W. Gräber, A. Kross, Vol.1, pp. 92-94.

[6] For instance, Maurines (1999b) considers as incorrect some students' answers which state that, when a non diffracting diaphragm is placed in front of a lens and illuminated by a plane wave, this diaphragm has no optical image, whereas it can be argued that nothing special happens in the conjugate image plane of such a diaphragm. Nothing changes on the screen when the diaphragm is moved : is this observation compatible with the understanding of image formation and the part of the lens as an imaging system ?

[7]B.S. Ambrose, P.S. Shaffer, R.N. Steinberg and L. McDermott, « An investigation of student understanding of single-slit diffraction and double-slit interference », American journal of Physics, **67** (2), 146-155.(1999) ; K. Wosilait, P.R.L. Heron, P.S. Shaffer, and L. C. McDermott, « Adressing student difficulties in applying a wave model to the interference and diffraction of light », Phys. Educ. Res., Am. J. Phys. Suppl., **67** (7), 5-15 (1999); M.C. Wittmann, R.N. Steinberg and E.F. Redish, "Making sense of how students make sense of waves", Phys. Teach. 37, 15-21 (1999).

[8]P. Colin,. « Two models for a physical situation : the case of optics. Student's difficulties, teachers' viewpoints and guidelines for a didactical structure » (Selected papers from the Second international Conference of the European Science Education Research Association (ESERA), Kiel, Germany, Kluwer Academic Publishers, Dordrecht , The Netherlands, 2000) (to be published).

P. Colin, « Two models for a physical situation : the case of optics. Students' difficulties, teachers' viewpoints and guidelines for a " didactical structure " » In *Proceedings of the Second International Conference of the European Science Education Research Association* (ESERA), Research in Sience Education. Past, Present and Future, 31 August - 4 Sept. 1999, Kiel, Germany,

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P. Colin, et L. Viennot, « Les difficultés d'étudiants post-bac pour une conceptualisation cohérente de la diffraction et de l'image optique », Didaskalia **11**, 89-114 (2000).
[9]This definition of an « image » should not be confused with the pattern of illumination, called « geometric image » by Wosilait and al. (1998), observed on a screen when an aperture is located between the light source and the viewing screen.
[10]The justification of the calculation could be based on the reversibility of paths of light. As shown in figure 3, a point source located at M emits a spherical wave transformed into a plane wave by the lens. But, once again, it should be stressed that the physical situation has completly changed. It is not a simple change in the propagation of light : the field is not at all the same, in particular in the plane where the holes are located.
[11] STTIS (" Science Teacher Training in an Information Society ") Symposium*:* « The innovative use of symbolic representations and informatic tools », in *Proceedings of the Second International Conference of the European Science Education Research Association* (ESERA), Research in Sience Education. Past, Present and Future, 31 August - 4 Sept. 1999, Kiel, Germany, edited by M. Komorek, H. Behrendt, H. Dahncke, R. Duit, W. Gräber, A. Kross, Vol 2, pp. 623-636.
[12]See, for instance, L.C. Mc Dermott, and P.S. Schaffer, « Research as a guide for curriculum development : An example from introductory electricity. I. Investigation of student understanding », Am. J. Phys., **60**, 994-1003 (1992).
[13]P. Colin, P. « Passage de l'optique géométrique à l'optique ondulatoire : l'idée de sélection par l'aval de l'information » (Unpublished report « Mémoire de tutorat », Université Paris 7-Denis Diderot, 1997 (on request.from LDSP)).
[14]M. Bertin, J.P. Faroux, J. Renault, Optique et physique ondulatoire. Optique géométrique et optique physique. Phénomènes de propagation (Cours de physique, Marketing, Paris, 1986), 3ème édition, pp. 221-224.
[15]Huygens' principle should be carefully used, not to confuse Huygens sources with classical point sources of geometrical optics. Thus, it is the status of the Huygens sources which is in discussion and, consequently, the status of the " object ". If the existence of fringes before the lens is admitted, which is not obvious because no sensor are located at this place to detect them, these fringes cannot be considered, according to us, as a " classical " object whose image is given by the lens. See below for further developments.
[16]R. Duffait, « Expériences d'optique, Agrégation de Sciences Physiques » (Bréal, Paris, 1997), p. 62.
[17]Concerning the students' story-like analysis, see, for example, S. Rozier, S. and L. Viennot, « Students' reasoning in elementary thermodynamics », International Journal of Science Education, **13** (2), 159-170 (1991); Maurines, L. (1999b) see Note 5.
[18]G. Kress, and T. van Leeuwen, Reading Images : the Grammar of Visual design (Routledge and Kegan Paul, London, 1996).
[19]See Ref. 8.
[20]See Réf. 12.
[21]For instance, in a photographic camera, it is the location of the film (with respect to the objective) that determines the elements of the scene which will be seen clearly on the photograh.

Philippe COLIN, Laurence VIENNOT
LDSP, Université Paris 7 - Denis Diderot, Case 7086
2 Place Jussieu
75251 Paris Cedex 05 France
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[22] Although « light rays » are commonly used, there is no consensus about its definition (see D.S. Goodmann, « General principles of geometric optics » in Handbook of Optics (M. Bass (ed. in chief), McGraw-Hill, USA, 1995) Vol I, pp. 3-109). Rays are often defined as line drawn in space corresponding to the direction of energy flow, more precisely, density of energy flow, i.e. to the Poynting vector. They are perpendicular to the surfaces of constant phase in an homogeneous medium and when these surfaces can be well-defined. What should be stressed is that « paths for (the calculation of) phase » should not be confused with routes for energy of the resultant field.
[23]See, for example, F. Goldberg, and L.C. McDermott, « An investigation of students' understanding of the real image formed by a converging lens or concave mirror », American Journal of Physics, **55** (2), 108-119 (1987).
[24] STTIS (" Science Teacher Training in an Information Society ") (1999a). Symposium: « Teachers' use of innovative Sequences », In *Proceedings of the Second International Conference of the European Science Education Research Association* (ESERA), Research in Sience Education. Past, Present and Future, 31 August - 4 Sept. 1999, Kiel, Germany, edited by M. Komorek, H. Behrendt, H. Dahncke, R. Duit, W. Gräber, A. Kross, Vol 1. pp. 441-457.
[25]See Ref. 8.
[26] Or, to be more precise, of « immediate acceptability », knowing that the consulted teachers were not , in any way, prepared to this particular discussion.