PROCEEDINGS OF SCIENCE

History of Sciences as a recourse to upgrade geometrical optics courses

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"Balzac disait que les célibataires remplacent les sentiments par les habitudes. De même, les professeurs remplacent les découvertes par des leçons. Contre cette indolence intellectuelle qui nous prive peu à peu de notre sens des nouveautés spirituelles, l'enseignement des découvertes le long de l'histoire scientifique est d'un grand secours. Pour apprendre aux élèves à inventer, il est bon de leur donner le sentiment qu'ils auraient pu découvrir." [1]

First year university courses in Physics, as we led them over years, do not seem to work out anymore [2]. Starting from this observation, we propose a reaction consisting in the rewriting and enrichment of these courses oriented by the idea of introducing the students to the original sense and motivation of their contents. As an example, we will present the structure of a course of basic geometrical optics focused on the essential part of the usual formal contents of geometrical optics, but which gives priority to discovery, self-investment and reflection. An ambitious objective that we try to get closer to by a structural interaction between the classic formalism of physics and fundamental questions arising from history of sciences.

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First of all, authors would like stress the fact that they are not researchers in Physics Education. First four authors are lecturers in Physics, working in Aix-Marseille Université (France), teaching in bachelor as well as in master programs. Last author is a CNRS researcher in the same university, dealing with History of Sciences, and more specifically with Arabic mathematics in the Middle Ages. All of them got to work together on a first year geometrical optics course. The proposal developped in this article is a consequence and an account of this common work. And as such, it tries to cope with local problems. However, we believe that some of the problems and solutions identified here respond to some kind of general criteria and could be applied elsewhere.

One origin of this work is the plain and uncomfortable feeling that for some reason, the way we were used to present our physics courses for years does not match with the students we have today [3], especially in the case of first year courses. It seemed crucial to us to question this situation. And as we are directly and daily confronted to it, to try and develop a concrete reaction.

And our reaction consisted in the rewriting of our courses, based on a structural interaction between the classic formalism of these physics courses and fundamental and genuine questions arising from history of sciences. With the essential aim of introducing the students by this means to the original sense and motivation of their contents [4]. And thus to develop their enthusiasm, curiosity, creativity and, we hope, their investment and success in their studies [5],[6]. In the following we will try to expose some of the guidelines of our work, via the example of an introductory course to geometrical optics that we wrote and gave for the last three semesters.

This course of geometrical optics, that was given in different and various first year bachelor programs over the last three years, corresponds to approximately thirty hours of teaching (including exercises and lab work), and it is composed of four parts entitled : *1. History of the rainbow [7]*, *2. How to start a fire with sun light*, *3. What does one see through a lens?* and *4. Seeing, seeing better, seeing bigger!* For matters of concision, we will focus here on the second course only.

The first guideline we have been following for developping this course is based on our feeling that in general, physics courses were taking the form of a teaching of results, through a series of very specific answers to questions that students had never asked themselves.

Indeed, the classical structure of a course in geometrical optics [8] will reveal us first that light can behave both as a wave and as a particle ; that its propagation is rectilinear, except if the medium is inhomogenous, or at the passage from a certain medium 1 to another medium 2. In which case, the light is deflected. But fortunately, the Snell-Descartes laws can tell us exactly how the light will be deflected, depending on the refractive or reflective nature of medium 2. And thanks to these basic laws, inhereted from illustrious scholars, and after a few pages of calculation, we will be able to realize our true goal and explain the way spherical mirors and thin lenses do work.

Here we would like to stress how artificial this way of presenting things is. Actually the point is to try not to read it with the eyes of a lecturer in physics, but through those of a student who knows nothing about the topic and never faced any of the so-called problems mentionned above.

Yet in the frame of a bachelors program recently developped in Aix-Marseille Université, called *Sciences and Humanities* – and which is a cross-disciplinary program dedicated to students coming from any secundary school background– we have been working on a very regular base for the last five years on a course dedicated to Light, Vision and Color. A course involving lecturers from extremely various disciplines - such as mathematics, psychology, chemistry, biology, philosophy, physics or history of arts. Working within this group, we slowly accepted and understood that by teaching rigorously and strictly the results of modern physics, and then applying those results to the resolution of some artificial problems, we were talking neither to the curiosity, nor to the intelligence of our students. And certainly not to their pleasure of understanding.

Gaston Bachelard actually wrote [1] that there is no doubt that it would be simpler to teach the results only. But that the teaching of the results of science is never a scientific teaching. Because if the line of spiritual production that led to the result is not made explicit, one can be sure that the student will combine this result with his own most familiar images. It is necessary for him to understand ; as one can only remember if he understands. So the student shall understand his own way. And as noone offered him reasons, he will add personnal reasons on top of the result.

Indeed, Bachelard suggests that the strict presentation of scientific results, laws, principles, could even happen to be counterproductive ; as students will necessarily and inconsciously fill the lack of justification and meaning by their own images and representations. Which will completely transform their knowledge and vision of our courses in a way that one cannot even imagine [9].

1. History of Sciences as a source of questionning

Consequently the first guideline for the writing of our geometrical optics course has been to get the students to ask themselves questions. To have them notice that the world is not obvious and filled with ready-made answers, but rather full of questions. That if one dares confronting those questions, he or she might find a real pleasure trying to answer part of them. And finally to focus on the fact that the world itself is rich of questions and problems. And that we don't need to build up weird exercises with pinguins running on an ice field before diving to catch a motionless fish, people fishing with a laser gun, or useless and simplistic optical intruments.

Questions are everywhere! Yet it is not easy to come up with a good question. A question that is relevant, not just anecdotic, that students could make theirs, but also that could help them build up progressively a knowledge anchored in reality. That is why, for finding good questions, we decided to turn to history of sciences and epistemology.

Being involved in the Sciences and Humanities bachelors program actually gave us the chance to develop a real collaboration between physicists, epistemologists and historians of science, for whom history of sciences is much less linear, logical, easy and self-satisfying than usually depicted in textbooks. But also much more demanding, torturous, complex, surprising, exciting and more human after all. Which makes it also much more credible in the end.

In particular, ancient texts, written back in the time when the answers of modern physics were not even suspected, and even before physics itself was existing as such, are a gold mine, filled with genuine, subtle, understandable and constructive questions on Nature. Refering to ancient texts - not in order to naively build up the myth that we are just dwarves standing on the shoulders of giants - but in order to enlight what were the real problems and questions that were facing scholars such as Aristoteles, Ptolemy, Ibn al-Haytham, Copernicus, Kepler or Newton, is a real and positive solution to open our courses to more culture, humanity and intelligence [10].

Let us now mention a few concrete examples of the contribution of philosophers and historians of sciences to the present geometrical optics course. Discussions between a physicist and a historian of mathematics on basic geometrical optics questions, brought to light the fact that a certain Ibn Sahl, by the end of the 10^{th} century, dedicated a book to the geometrical study of the ideal shape of optical burning instruments [11]. Those are instruments that could set objects on fire by concentrating all the light rays they would collect in an exact single point. Ibn Sahl considered those light rays either as diverging form a single point source close by, or as a beam of parallel lines issued from a single point situated extremely far.

And not only did Ibn Sahl compute that an ideal miror would have an elliptic shape for a close by source and a parabolic shape for a far away source. Not only did he compute the exact position of the focus. But he did the exact same thing for the case of lenses. And found precisely the same results that Descartes published six hundred years later. Meaning that Ibn Sahl apparentely already detained a prototype of the law of refraction [11].

Besides the surprise that can cause this information and its interest as a mere fact of history, it also made us realize that this question of setting things on fire with sun light, was actually a genuine scientific question, that had been driving research for centuries (Ibn Sahl is not an isolated example). But also a clever, simple, concrete, and appealing question, that could grasp the attention of students from different horizons. And that organizing a course around this question could certainly allow us to build on a much stronger basis some notions. Such as the object infinitely far away, parallel light rays, angular diameter and focus obviously. Notions that are extremely basic but also fundamental. And that we had noticed for years that students would not understand. Indeed very few students could give a clear definition of the focus, which was just for them a mysterious point on the axis, which had well known geometrical properties, but no physical meaning at all.

Therefore a whole geometrical optics course was written on this precise topic by a physicist. And then read by the historian of mathematics. And it occured that this reading stressed up a fact that we all already know but underestimate too often. That is the huge number of approximations that are present in a physics course. To physicists, approximations are natural ; that's the core of their job. Making reasonnable approximations that students do not understand. And one can see that they do not understand. But what do we, teachers, do about it ? We usually repeat the same words students already had not understood, at best in a different order. Obviously, the course has been written to be as clear, complete and rational as possible. So it is very difficult to imagine a better way of answering to a student than the one that was already used in the presentation he just did not understand. Having a researcher from another discipline, who is aware of the physical topic, saying that he is shocked by the number of approximations he has to accept in order to go through our course, forced us to realize how serious was the problem. How inexorably our way of explaining things was narrowed by our over-specialization and could not satisfy a beginner student.

The solution we chose in this particular case was to stand together in the classroom in order to introduce the concept of spherical lenses. The historical burning purpose of the instrument and the exact solution of the planar-hyperbolic lens was presented the way Ibn Sahl had solved it a thousand years ago. And then only, the approximation of the spherical lens was introduced.

Solving the original complete problem is obviously far from easy for a first year student. But following the whole strict demonstration that leads to determine the shape of a perfectly stigmatic lens for an infinitely far point source, in order to determine the ideal burning optical instrument, and finding out that one side of the lens must be planar and the other one hyperbolic is absolutely feasible. All the more that it is here motivated by a purpose that we expect they can make their own. And we had the feeling then, as we got into the regular contents of the course and introduced thin, spherical lenses, and limited the study to the paraxial approximation, and when we proposed

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to evaluate those approximations by comparing this result to what a hyperbolic lens would give, that for the first time in our course, students had the opportunity to get a global view of the problem. To understand the limits of the study we were making, and to see that we were working in a certain restrictive frame, that would always be there in physics and that they would have to keep in mind.

A final example is the one of the law of refraction, on which is based most of the course of geometrical optics, but that still many students manage not to understand by the end of the course. Some can use it. But hardly any can explain the physical meaning of the index, the reason why there is a deviation, and a significant proportion of them cannot place the angles of incidence and refraction properly. One more time, going through the ancient works of Ibn Sahl, who gives a geometrical representation of the law of refraction can help. As well as presenting the way Descartes himself wrote the law and justified it using the metaphor of bouncing balls [12] – even if his demonstration is mechanically wrong. We believe that this allows students to read the law in an all new perspective, and helps them understand that there is meaning behind equations and symbols. And that these equations were not found carved in stones. That they could be written differently, and that they were developped by people who had in mind a certain problem that they wanted to solve, which shines an all new light on the result.

It is surprising to read for instance, that this very simple and classic experiment of isolating a *light ray*, directing it towards a block of glass, measuring the angles of incidence and refraction and comparing their sinuses – experiment that we all did during our studies in order to *demonstrate* the law of refraction – was never made by Descartes himself. Who claims that he actually only made one experiment on the topic : he asked a glass blower to realize a lens that would be planar on one side and hyperbolic on the other one, placed it in the sunlight and checked that light rays would all focus in a single tiny spot which position he had exaclty predicted thanks to the law. And that experiment was enough for him [13]. We think this rises very interesting epistemological and historical questions on what was a scientific proof back then, and how this apparently obvious concept nowadays was not necessarily shared by our predecessors. And we think it is important sharing this information with young students, for it is good for them – and for society – to realize that science is a moving thing, and that it relies on concepts, implicits and methodologies that do not come as given, and that are worth questionning.

2. History of Science and lab work

In this last part, we would like to adress another very efficient way of both confronting students with problems and making use of history of science as a tool for a thorougher teaching of physics.

In general, students get to do some lab experiments once the theoretical course is over. In order, supposedly, to apply practically what they were told during the course. Lab experiments are extremely good pedagogical tools. But only if one manages to get the students to get invested and curious about them [14]. Otherwise it's a failure. And checking that the formulas that were given in the course are actually right, is a boring work to do that most of them will not benefit from. We do not claim that lab works as a conclusion to a course should be banned. But we highly support the development of introductive lab work, coming before any theoretical course on the topic.

In the frame of these courses, we developped a series of such lab works in geometrical optics, based on real historical experiments, including one on the historical theories of refaction, one on

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Galileo's telescope and one on the camera obscura (or pinhole camera).

In particular, those last two instruments were historically used before they were understood. Indeed, Galileo had no precise idea of the law of refraction itself. And people could observe moving images at the back of pinhole cameras and even used them for painting, long before their formation could be explained. Yet Galileo could measure the magnification of this telescope and improve its optical properties [15]. And the use of the pinhole camera was a determining factor in the understanding of Vision by Kepler [16].

Working on those very simple systems is first the ideal way to let the students understand before the course that a lens is a real 3D piece of glass with a peculiar shape and not just a line terminated on both sides by arrows. That a focus is the place where you should place a flammable object in order to ingnite a fire thanks to sun light, and not just another point. That an image is a 2D and dynamic thing, that can be seen both on a screen and straight with your eye through the lens, and that a vertical arrow is just an extremely simplified symbol for an image.

Second, these problems are exciting and intelligent problems. Indeed, it proved to be extremely exciting for students to see enlarged images of distant objects with just two pieces of glass and a tube. As it was for them to see moving objects projected at the back of the camera obscura. It is not a common thing to see students running and laughing through the lab because they want to write down something they understood. Neither it is to hear a first year student screaming ”That's so great !”, ”Why did not they present us physics like that before?" or ”Can you thank for us the people who built these cameras for us ?” Yet we have heard such things on a weekly basis for the last two years. Intelligent, real and elegant problems are exciting, even for our students.

And excited students are active and awaken students. And if one gives them the time to think about those problems, they will spontaneously try to understand them. And they can actually do it without a very heavy theory. This is actually how it historically worked. As Galileo showed, you can very easily measure the magnification of a telescope by observing a series of pairs of squares of inequal sizes, watching the big squares with your naked eye, and the small one through the telescope [15]. You can change the lenses and see how magnification changes with the lenses. You can even guess that the ratio of focal lengthes is playing a role. All of that on your own. A significant indicator of the enhanced investment of the students and of their general ability to take relevant conclusion of their own is certainly the fact that the average length of their written reports of such lab works is three to four times longer (25 pages) to what we were used to (6 to 8 pages).

But a third point is that students will also realize very quickly that if they do not want to stick to a qualitative point of view and if they want to quantify phenomena, to predict the exact value of the magnification, the ideal length of their telescope, the real size of an object whose image appears on a screen, they need mathematics. They need those laws and formulas that are in the courses. And this simply means that students then enter the course knowing what they look for. They are looking for the law or theory that can help them answer their questions. And when the law comes, they know what it means and one thing they can do with it. Because it is exactly the piece they were missing before the course. Can one dream of better teaching conditions ?

3. Conclusion

We do not claim here that the method we presented is necessarily working better than any

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other. And we don't claim that it should be generalized either. Specially because we have little way of measuring its success, and because we do not have an idea of what will be left in students' mind in several years. Yet we can say, that this way of teaching physics gave a whole new meaning to our practice as lecturers, and that we took a real lot of pleasure changing our habits. We have the feeling that this pleasure was noticed and shared by students. And we noticed that this pleasure was going along with a better understanding of phenomenas and a much deeper investment in their courses as compared to what we were used to. Which according to us is more than enough to justify all the efforts done.

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