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Newton and Colour: the Complex Interplay of Theory and Experiment

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ABSTRACT. The general aim of this paper is to elucidate some aspects of Newton's theory of light and colours, specially as presented in his first optical paper of 1672. This study analyzes Newton's main experiments intended to show that light is a mixture of rays with different refrangibilities. Although this theory is nowadays accepted and taught without discussion it is not as simple as it seems and many questions may arise in a critical study. Newton's theory of light and colour can be used as an example of the great care that must be taken when History of Science is applied to science teaching. An inadequate use of History of Science in education may convey to the students a wrong conception of scientific method and a mythical idea of science.

1. INTRODUCTION

It is nowadays assumed that the use of the history of science may improve the teaching of science. Accordingly, there has been an increasing use of history of science by teachers – both at high-school and university levels. In the specific case of physics, the development and status of uses of history of physics in education has been recently reviewed (Bevilacqua and Giannetto 1996).

There are, however, some pitfalls on the way to this approach. The history of science can be misused (as anything else) and lead to a mistaken view of science. The general aim of this paper is to elucidate some of those dangers and to show that, given suitable precautions, the history of science may indeed help science teaching. Great care, however, must be taken to ensure adequate use of historical resources in education.

Instead of discussing those dangers in an abstract way, this paper will focus upon one recent attempt to apply History of Physics to education: Dudley Towne's use of Newton's colour theory (Towne, 1993). Towne used Newton's 1672 original presentation of his theory, together with experiments and other aids, in teaching beginning, nonscientist students. He claimed that Newton's work is clear, easy (and even 'delightful') to read and understand. He stated that the original paper is a model for the presentation of the scientific method. He also emphasized how easy it is to draw the correct inferences from Newton's experiments.

Both the analysis of Newton's work and its educational use as presented by Towne are highly problematical. Newton's arguments are not as straightforward as they seem. Besides, the interpretation of scientific

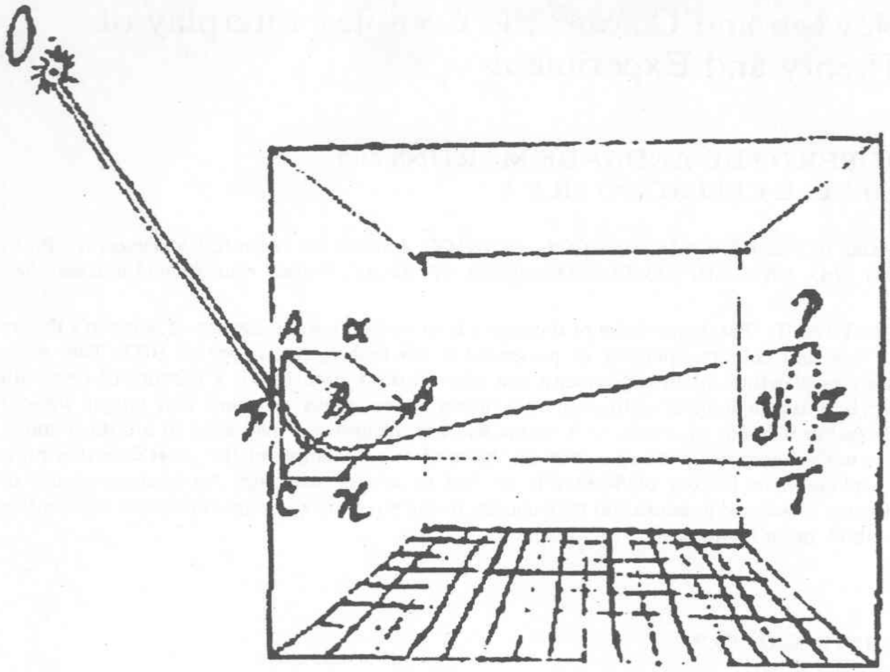

Figure 1. Newton's scheme for the first experiment in his 1672 paper.

method implicit in his paper is at variance with current historical and philosophical knowledge.

The general aim of this paper is to elucidate Newton's work and to show how it may improve science teaching.

2. THE DEFLECTION OF LIGHT BY A PRISM

In a paper published in 1672 (Newton 1672a), Newton presented his concept that light is a 'heterogeneous mixture of differently refrangible rays' – each colour corresponding to a different refrangibility. He presented several experiments to corroborate this theory. In the first one (Figure 1),[1] a beam of sun light passed through a prism and formed a spot[2] on the wall of his chamber. He noticed that the spot was not circular as the disk of the sun – it was oblong (Kuhn 1978, p. 35; Lohne 1968, p. 172). To explain this effect he assumed that the white light of the sun was composed of many different rays. Each kind of ray is refracted in a different direction and is associated with a different colour: 'the least refrangible rays are disposed to exhibit red colour, and (. . .) the most

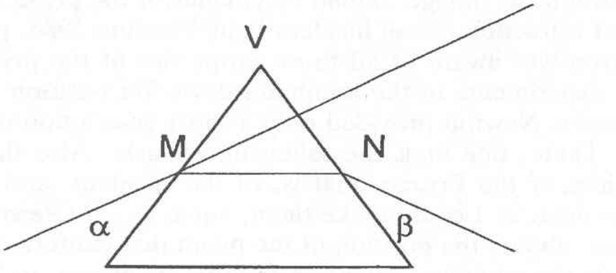

Figure 2. A prism in the minimum deviation position.

refrangible rays are all disposed to exhibit a deep violet colour' (Newton 1672a, p. 53).

One important fact in favor of Newton's theory was his *Experimentum Crucis*. In this experiment, light passed through two prisms. The first one produced a coloured spectrum and the second was used to study the deviation of each colour. The experiment showed that each colour of the spectrum suffered no further division at the second prism, and that each colour was deflected at a different angle.

In modern textbooks either the first or both those experiments are usually introduced as sufficient evidence for Newton's theory of composition of white light.

3. THE MINIMUM DEVIATION POSITION OF THE PRISM

When Newton described the single prism experiment, he remarked that the spot projected on the wall should be circular and not oblong, according to the 'received laws of refraction'.

Why did Newton state that he expected that the 'image' should be circular? Ask this question to undergraduate physics students, and you will notice the difficulty of that point. To understand what Newton meant, it is necessary to take into account the details of his experiment and some *implicit* considerations concerning the exact position of the prism.

There is one single position of the prism that would produce a circular 'image', according to the Cartesian law of refraction. It is the so-called 'minimum deviation' position. If the prism is slowly rotated around the axis that passes through the centre of the triangular faces, one observes that the direction of the deflected beam changes. There is one special position where the angle between the initial direction of the beam and its direction after passing through the prism is a minimum. In this position, the incident and refracted beams make equal angles with the sides of the prism (Alonso and Finn 1972; Figure 2). It is possible to prove that at this position the 'image' should be circular, if the prism exhibited a single index of refraction for all incident light (Newton 1984, pp. 53–54).

Newton was aware of all those properties of the prism and made his colour experiments in the minimum deviation position. However, in his 1672 paper, Newton provided only a short description of the first experiment.[3] There, one finds the following remark: 'Also the Refractions on both sides of the Prisme, that is, of the Incident, and Emergent Rays, were as near, as I could make them, equal (. . .)' (Newton 1672a, p. 49). As stated above, the position of the prism that conforms to this condition is exactly the minimum deviation position. However, in his paper Newton neither stressed the importance of this position, nor did he state that only in this position one would expect a circular 'image', according to the 'received laws of refraction'.

Did Newton know all that in 1672? In his published articles of that time he presented neither a proof similar to the one provided in the *Lectiones opticae* nor even the simpler one published in the *Opticks* (Newton 1704, p. 49). However, he clearly stated in the 1672 paper that he *computed* the angle between the rays coming from the Sun after they passed through the prism 'and found, that the emergent Rays should have comprehended an angle of about 31′, as they did, before they were incident' (Newton 1672a, p. 49). However, the measured divergence of the deflected beam was 2° 49′ instead of 31′. The discrepancy between the predicted and observed angle required an explanation, and Newton's theory provided it.

All this shows that the minimum deviation position is a necessary condition of Newton's first experiment.[4] On the other hand, if one reads critically the 1672 paper, it becomes evident that Newton's article is far from being clear and didactic, since Newton did not make it clear that the minimum deviation position of the prism was important. He also did not tell how to find this position (Sabra 1981, p. 237).

4. MISUNDERSTANDING OF NEWTON'S PAPER

When Newton published his first paper, many people were unable to understand that the whole argument depended on the choice of the minimum deviation position. The first critic of Newton's theory was the French priest Ignace Pardies.

Pardies stated that two rays that arrive at the prism would suffer no change in their relative angles in planes parallel to the axis of the prism. However, in a plane perpendicular to the axis, the angle after passing through the prism might be different from the initial angle. To substantiate his claim, Pardies presented the detailed computation corresponding to a special position of the prism. He concluded that two rays arriving at the first surface of the prism encompassing an angle of 30′ might leave the prism forming an angle of more than 3°, depending on the angle of incidence (Pardies 1672a, p. 87)[5].

In his answer to Pardies, Newton accepted the method and computations of the priest. However, he remarked that in his own experiment and calculations, he had assumed that the incident and emergent rays had equal inclinations relative to the sides of the prism, whereas in Pardies' calculation the angles were widely different:

> But the Rev. Father is under a mistake. For he has made the refractions by the different parts of the prism to be as unequal as possible, whereas in the experiments, and in the calculation from them, I employed equal refractions (Newton 1672b, p. 90).

Newton then presented a general (geometric) proof that when his experimental conditions are satisfied, the angle of the deflected rays should be equal to that of the incident rays.

Once Pardies understood the required conditions of the experiment, he agreed with Newton that the 'image' should be round, according to the usual optical theory. Pardies' behavior shows that he did not understand from Newton's first paper that the minimum deviation position was a crucial condition. It also shows that Pardies' criticism was not as silly as it seems at first sight.

Let us now consider Towne's account of Newton's first experiment. Nowhere in his article does he refer to the relevance of the minimum deviation position. On the contrary: in his footnote 7 he says that 'although it is not essential to do so for any of the experiments described in Newton's paper, to preserve a sense of reproducibility it is advisable to turn the prism so that some colour is at minimum deviation'. That is wrong. If the prism were not in this position in the first experiment, nothing could be concluded from it – as shown by Pardies.

5. ELIMINATION OF DIFFERENT HYPOTHESES

After one understands the theory behind Newton's first experiment, it is possible to grasp his first conclusion: the facts are in disagreement with the accepted theory of refraction. What else could be concluded from this experiment?

Towne stated that this experiment alone is sufficient to conclude that the light of the Sun was heterogeneous:

> (. . .) the oblong shape of the spectrum can be measured with a ruler, and is sufficient evidence for the declaration that light consists of 'difform rays, some of which are more refrangible than others'. (Towne 1993, p. 115)

It was *not* possible to conclude that, since other explanations were possible. Indeed, both Newton and his contemporaries (Pardies, Hooke, Huygens, etc.) suggested *several* explanations for this effect. In the 1672 paper, Newton explored many conjectures that occurred to him. He tested whether the oblong shape of the spot could be due to the different thickness of the prism, or to the size of the hole, or to the position of the prism (inside or outside the dark room). In all those variations of the first experiment, the spot remained oblong. Newton then devised a second experiment:

> Then I suspected, whether by any *uneveness* in the glass, or other contingent irregularity, these colours might be thus dilated. And to try this, I took another Prisme like the former, and so placed it, that the light, passing through both, might be refracted contrary ways, and so by the latter returned into that course, from which the former had diverted it. For, by this means I thought, the *regular* effects of the first Prisme would be destroyed by the second Prisme, but the *irregular* ones more augmented, by the multiplicity of refractions (Newton 1672a).[6]

The test showed that the spot was now circular. So, the irregularities of the glass were not the cause of the oblong shape.

Another interesting conjecture of Newton's was that light might travel in *curved* lines after passing through the prism. If light travels in a straight line, and if the hole is of negligible size, the dimensions of the spot will be proportional to the distance between the hole and the screen. If one takes into account the dimensions of the hole, then it is the *difference* between the dimensions of the spot and the diameter of the hole that should be proportional to the distance – as Newton indeed observed. So, light travels in straight lines after passing through the prism (Newton 1672a, p. 50).

In Newton's *Opticks* there is a much clearer presentation of the evidence. The second proposition of part 1, book 1, states that 'The light of the Sun consists of rays differently refrangible'. In the proof of this proposition, Newton presented his experiment of the oblong spot, but afterwards remarked:

> So, then, by these two experiments it appears that in equal incidences there is a considerable inequality of refractions. But whence this inequality arises, whether it be that some of the incident rays are refracted more, and others less, constantly, or by chance, or that one and the same ray is by refraction disturbed, shattered, dilated, and as it were split and spread into many diverging rays, as Grimaldi supposes, does not yet appear by these experiments, but will appear by those that follow (Newton 1704, p. 34).[7]

After this remark, Newton presented experiments #5 to #10 (Newton 1704, pp. 34–61), together with many variations and commentaries, before he concluded the proof of the proposition. Therefore, Newton himself clearly perceived that the first experiment was not sufficient to prove that the light of the Sun contains 'rays differently refrangible'.

After eliminating several alternative explanations, Newton presented a new important experiment. He called it the *Experimentum Crucis* – an obvious reference to Francis Bacon – and he probably intended it to be decisive.

6. THE 'EXPERIMENTUM CRUCIS'

A planned experiment is always undertaken after theoretical analysis. The naive belief that one must go to the laboratory with an 'empty mind' or that 'experiments talk by themselves' (as Towne's paper puts it) is an old scientific myth – and here 'myth' means 'outside reality'. When Newton undertook his study of colours, he was deeply concerned with a few theories about light. He was trying to find out which one was correct. Theory guided experiments – not the converse.

As Newton tells us, he was not the first one to observe the colours produced by a prism. Indeed, he stated that 'I procured me a Triangular glass-Prisme, to try therewith the celebrated *Phænomena of Colours*' (Newton 1672a, pp. 47–48). It was well known that prisms produced an effect similar to a rainbow – the phenomenon was described by Robert Boyle, René Descartes, Robert Hooke (Boyle 1664; Descartes 1637; Hooke 1665) and several different authors of that time. Several explanations had already occurred to many people.

In Newton's first experiment, the oblong shape of the spot was produced by different colours. Each colour emerged from the prism in a different direction. Nowadays, we interpret this as a *separation* of colours that are already present in white light. However, that was not the only (or even the most 'intuitive') interpretation.

The first idea that occurred to everybody – including Newton himself – was that the prism *produced* colours – that is, white light was *transformed* into a set of colours. Indeed, white light always seemed to be the simplest kind of light. When light passes through a transparent or translucent coloured body it acquires colour – and this seemed a *transformation* of light. In the same way, it was believed that the prism *created* the colours – it was not just a *separation* of colours.

When Newton published his studies of light and colour, Hooke's *Micrographia* (published in 1665) was an influential work. Hooke had presented in that book a very obscure theory about the transformation of white light when it is obliquely refracted.

In his 1672 paper, Newton had already arrived at the 'correct' conclusion: each spectral colour has fixed, unchangeable properties; and each colour has a specific refrangibility.

In Newton's theory, the least refrangible rays correspond to red and the most refrangible correspond to violet. This is a delicate point of Newton's theory. The relative refrangibilities of different colours vary in different substances. It is possible to find transparent bodies that deflect blue and violet light less than red light – contrary to Newton's belief.

Newton's idea that white light is not simple but a mixture of all colours is not intuitive. It did not arise at once in his mind, but evolved slowly from his intensive work. The main point was to find out whether colours can be transformed and created or not. This is the central aim of Newton's *Experimentum Crucis* (Lohne 1968).

In that experiment, a beam of solar light passes through a first prism and strikes a board with a small hole in it, so that only a small portion of the spectrum (a single colour) passes through it. This secondary beam reaches a second prism. Newton observed that the second prism did not change the colour of the secondary beam. He also noticed that different colours presented different deflections in the second prism: the red light suffered again the least deviation, and violet the greatest (Newton 1672a, pp. 50–51).

Newton compared this experiment to what happened in the case of white light in a single prism: different colours appear and each colour is deflected in a different direction. His explanation was that white light consists of a mixture of all colours that appear in the spectrum, each colour being separated from the others – but not created – by the prism, because of their different refrangibilities. This hypothesis also explained the oblong form of the spot in the first experiment:

> (. . .) the true cause of the length of the image was to be no other, then the *Light* consists of *Rays differently refrangible* which without any respect to a difference in their incidence, were, according to their degrees of refrangibility, transmitted towards divers parts of the wall (Newton 1672a, p. 51).

The relation between colour and refrangibility stated by Newton did not cause great controversy. The problematic question was the composition of white light. The statement that white light is a 'Heterogeneous mixture of differently refrangible Rays' led to a strong controversy between Newton and Hooke, Huygens and Pardies (Sabra 1962).

For Hooke, white light was a simple kind of vibration and coloured light was a modification of white light. He supposed that light was some kind of non-periodic wave that would acquire different properties near the edge of the light beam. Hooke believed that the wave front would become inclined relative to the direction of propagation when light was obliquely refracted – as in a prism. The extremity of the wave front that came first would become red and the end extremity would become blue. Near the prism we do not observe all spectral colours. We see exactly what Hooke describes: a white beam with small blue and red fringes on opposite sides.

If one observed the beam very far from the prism, the red and blue regions would expand and overlap. Hooke believed that all colours were produced by the blending of blue and red. So, it was possible to explain the colours produced by the prism.

In answer to Hooke's letter (Hooke 1672) Newton presented many experiments to show that white light is a mixture of different rays (Newton 1672c). In the 1672 paper, he had already combined the colours produced by the prism with the aid of a converging lens and produced white light.

> (. . .) all Colours of the Prisme being made to converge, and thereby to be again mixed as they were in the light before it was Incident upon the Prisme, reproduced light, intirely and perfectly white, and not at all sensibly differing from a *direct* Light of the Sun, unless

> when the glass, I used, were not sufficiently clear; for then they would a little incline it to *their* colour. (Newton 1672a, p. 55)

The plan of Newton's experiment may be found in Newton's original drawing published in the 1672 paper. Towne referred to this experiment, but the conception of his drawing is unintelligible (Towne 1993, p. 115). It presents a parallel beam that becomes divergent without apparent cause. The beam leaving the prism is divergent, not parallel as he represents it. It will be difficult for any student to understand that drawing. It would be better to use Newton's original scheme, as it is much clearer than Towne's.

The composed white light produced by Newton was visibly equal to solar light. Nevertheless, neither this experiment nor the *Experimentum Crucis* proved that this resulting light was really equal to solar light. It could happen – as Hooke believed – that the white light of the Sun was simple, and that the different modifications of white light (the several colours) could be combined to produce another kind of white, by mutual compensation of their differences.

In all of Newton's experiments, light is refracted at least once. It could happen that the refracting medium acted upon light by changing it, in such a way that this modification remained unchangeable in subsequent refractions.

The choice between Newton's theory and the 'modification theory' could not be decided by experiment alone. Indeed, it was impossible to perceive the existence of all colours in white light, before it was refracted. Hence, it was always possible to maintain that, before any transformation, white light is simple and not composite.

Newton at last perceived that the distinction should be grounded upon methodological arguments. In his answer to Hooke, he said:

> I see no reason to suspect, that the same *Phænomena* should have other causes in the Open Air. (Newton 1672c, p. 134)

This means that he saw no reason to introduce a distinction between two kinds of white light, if they exhibited the same properties in all experiments. One should not multiply entities if this is not necessary: one should choose the simplest theory, according to the methodological rule known as *Occam's razor*.[8]

Returning to Towne's paper, one sees that it does not discuss those questions.

He states that

> (. . .) the simplicity of the experiments and the order in which Newton presents them allow the theory to form in the reader's mind before Newton makes a formal statement of the hypotheses. (Towne 1993, p. 113)

According to Towne, students will be led to the same theory as Newton and will conclude that white light is a mixture of rays. However, it was shown above that this conclusion is not straightforward and that there are other possible interpretations of Newton's experiments.

7. CONSTANCY AND COMPOSITION OF COLOURS

An important part of Newton's argument is contained in his experiments intended to show that spectral colours cannot be transformed into different colours. In his first paper Newton already stated the immutability of colours. He made several experiments intended to modify them and never observed any change. In his experiments he

> (. . .) refracted it with Prismes, and reflected it with Bodies, which in Day-light were of other colours; I have intercepted it with the coloured film of Air interceding two compressed plates of glass; transmitted it through coloured Mediums, and through mediums irradiated with other sorts of Rays, and diversly terminated it; and yet could never produce any new colour of it. (Newton 1672a, p. 54)

The *Experimentum Crucis* showed that a second refraction did not decompose the colours that came from the first prism. It was also necessary to show that when pure light (e.g. a spectral red light) is diffused by a coloured body (e.g. a blue paper) or passes through a transparent coloured glass its colour does not change – it only suffers an intensity change. Additional experiments devised by Newton to show that spectral colours do not change in those conditions were highly relevant to support his claim of the constancy of pure colours.

According to Newton's theory, coloured bodies do not transform the colour of the light they receive: they act as filters, allowing some colours to be reflected and absorbing other colours. Newton stated that the colours of natural bodies

> (. . .) have no other origin than this, that they are variously qualified to reflect one sort of light in greater plenty than the other. (. . .) that means any body may be made to appear of any colour. They have there no appropriate colour, but ever appear of the colour of the light cast upon them, but yet with this difference, that they are most brisk and vivid in the light of their own day-light-colour (Newton 1672a, p. 56).

This is another very important point of Newton's theory that Towne was unable to grasp. To illustrate this theory, Towne suggested an experiment that contradicts Newton's concept. He stated that two strips of blue and red paper illuminated by the spectrum will appear black and then turn into white depending on the part of the spectrum that shines upon them.

According to Newton's theory a paper will appear white if it reflects light of all colours of the spectrum, in a proportion similar to that of the Sun's light. This can never occur in the suggested experiment and therefore the strips of paper would never appear white. Besides, a paper will appear black if it absorbs most or all incident light. This would not occur with common blue or red paper under red or blue light – as stated in the suggestion. They must look dark but will reflect a small part of the incident light.

In the 1672 paper, Newton described experiments with red and blue pigments. When he threw different colours of the spectrum upon those pigments, he observed that they appeared of the same colour used to illuminate them, although they appeared more bright when their natural colour was cast upon them.

8. PRIMARY AND COMPOUND COLOURS

To understand Newton's argument, it is also necessary to stress his concept of simple (or primary) colour. Our common sense accepts that colours can be changed in several circumstances, such as in the case of mingling pigments or beams of light. If we regard colour as the qualitative property of light perceived by our senses, colour can indeed be changed. It is possible to produce orange colour from yellow and red paint. So, according to common sense, colours are not immutable as Newton asserted.

To develop his theory, Newton created a new concept of colour. He distinguished between our sensation and the properties of light itself. He carefully stated that different rays of light have different 'disposition to exhibit this or that particular colour'. The same kind of light always produces the same sensation, but the same sensation is sometimes due to different kinds of light.

Newton introduced a theoretical distinction between simple (or primary) colour and compound colour. The first one (primary colour) corresponds to a homogeneous light, one that cannot be decomposed into different components. The second one (compound colour) corresponds to a heterogeneous light, one that can be decomposed into different components. Our eyes cannot distinguish primary from compound colours: they may look exactly alike.[9] However, the two kinds can be distinguished by experiment: compound light can be decomposed in two or more components by a prism. Primary light cannot be so decomposed.

It follows from this *definition* that white light is not simple or primary. It is compound, since it may be decomposed into several different colours by a prism.

Now, it might seem as though Newton was merely playing with words: if he *defined* in this way simple and compound colour, it follows *from the definition* that white light is not simple. So, the whole question is reduced to a choice of definition. It seems that Newton did not need much to attain his objective.

This, of course, is an oversimplification of the problem, but that is the way it is understood by most students and – unfortunately – by teachers. If one accepts Newton's definition, then *one single experiment* – the 'decomposition' of white light by a prism – is sufficient to prove that white light is compound.[10]

One must remark, however, that definitions and distinctions are not arbitrary. Newton proposed a dichotomy between primary and compound colour (or light). This dichotomy is philosophically adequate if any colour (or light) can be exclusively classified *either* as primary *or* as compound, but *never* as both or neither. His concept will be *useful* if both sets are not empty. Only experience can show whether it is adequate or not.

The *Experimentum Crucis* is instrumental in showing that there are, indeed, pure colours. If one separates from the coloured spectrum a narrow beam of light, its colour will not be changed by a second prism. Besides, it is also necessary to show that this colour cannot be decomposed or altered by other means (for instance: by passing it through a coloured glass).

It is also necessary to test whether the concept of compound colour holds water. Suppose one joins two pure beams of light (for instance, red and yellow), producing orange light. According to the *concept* of compound colour, this orange cannot be pure or primary. However, only *experience* can show whether this orange light will be decomposed by a prism. It could happen (in principle) that the combination of two different primary colours would, in some cases, yield another different colour that could not be decomposed by a prism.[11] For this reason, Newton had to test this, too. So he did, and he observed that the simple colours used to form a compound colour could be always retrieved again by passing the compound light through a prism.

Several other points of Newton's work could deserve discussion. Let us, however, discuss the moral of this history.

9. HISTORY OF SCIENCE AND EDUCATION

There are several ways of using history of science as an aid in teaching. The choice depends on the educational aim and on the kind of students in view. The public may include science students, future teachers, non-scientists, etc. The aim may include learning scientific theories and concepts, the nature of science and its method, the relation of science to its social context, and so on.

The use of history of science has been particularly popular among people who address non-scientists (Gross 1980; Hetherington 1982). This is the specific case of Towne's use of Newton's work on colour. It seems that his aims in using Newton's paper were:

- to exhibit a particular concept of (inductive) scientific method;
- to show that scientific works can be clear and interesting even when read by non-scientists;
- to teach some physics (the classic theory of colours).

Let us discuss each of these points in turn.

9.1. *Scientific Method*

Physics teachers (even at university level) sometimes do not understand the nature of science. There is still a widespread belief in an inductivist model of scientific inquiry, of the worst positivist kind (Abimbola 1983; Hodson 1985). Teachers who do not have interest and competence in history and philosophy of science will usually transmit a distorted view of the scientific enterprise to their students (Matthews 1988). They may try to show how one gets a theory from observation and experiment or how one can *prove* a theory – notwithstanding the philosophical impossibility of both attempts. Sometimes they are not aware of their lack of understanding and even try to use history of science to improve their teaching. However, the kind of history of science they use is distorted and oversimplified – the kind of thing historians of science call 'Whig history' (Brush 1974; Siegel 1979).

The careful study of history of science can teach a lot about the nature of science. Pumfrey (1991), for instance, lists a few important components of the contemporary view of scientific endeavor:

1. Meaningful observation is not possible without a pre-existing expectation.
2. Nature does not yield evidence simple enough to allow one unambiguous interpretation.
3. Scientific theories are not inductions, but hypotheses which go imaginatively and necessarily beyond observations.
4. Scientific theories cannot be proved.
5. Scientific knowledge is not static and convergent, but changing and open-ended.
6. Shared training is an essential component of scientific agreement.
7. Scientific reasoning is not itself compelling without appeal to social, moral, spiritual and cultural resources.
8. Scientists do not draw incontestable deductions, but make complex expert judgments.
9. Disagreement is always possible.

It is easy to perceive that the analysis of Newton's 1672 paper presented in this paper provides an example of most of those components of the nature of science. However, this cannot be achieved by the mere reading of Newton's 1672 paper. It is necessary to *discuss* it and to *read it in the light of its context*.

It is very misleading to study a detached piece of scientific work, without a knowledge of its context. For this reason, a teacher who is not fully conversant with the context had better use 'case studies' produced by professional historians of science – such as Conant's (1966) *Harvard Case Histories in Experimental Science* – rather than attempting to use a detached piece of primary source. A fine scientific appreciation of Newton's 1672 paper requires some knowledge of Newton's other works on optics, and also some knowledge of previous and contemporary optical studies by other researchers. Depending on the aim, it will be necessary also to study the philosophical, technological and social contexts behind Newton's work. Only in this way can a nice picture of the scientific practice emerge.

9.2. *Science for Non-scientists*

Many science teachers are eager to show that science is not an esoteric discipline: anyone may understand and enjoy science. There is some truth in this statement: anyone may understand and enjoy *some part or aspect* of science. However, science itself **is** an esoteric discipline – exactly as music, for instance, is. Most people can enjoy music, but only a few persons are able to understand its structure, to play it well or to compose good music. To be a competent piano player, any person must undergo a technical training that may last for many years. To become a good composer, the training will be even more difficult and sometimes painful. The same kind of thing occurs in science. One should not present scientists as demigods (it is always nice to remember that scientists are human and fail). On the other hand, the difficulties of scientific training should not be underestimated.

When teaching physics to non-scientists, there is always the danger of presenting some kind of 'watered-down science', which avoids difficult aspects – such as measurement, equations, complex arguments, and so on. There are, indeed, many interesting things about science that can be learned without entering into technical details. It seems, however, that history of science is not the best way to present the simple aspects of science. Of course, one can use the 'external' history of science to discuss issues such as the relation between scientific and technical development without the analysis of 'difficult' aspects. However, if one intends to teach science itself through the history of science, it will be impossible to avoid technical details. Indeed, it may be easier to present or to learn a textbook version of any scientific subject than to present or to learn its conceptual history.

9.3. *Scientific Knowledge*

There is an important distinction between scientific *knowledge* and scientific *belief*. A person has scientific knowledge about some subject if he knows the scientific results, accepts this knowledge, and *has the right to accept it*, because he knows how this knowledge was justified and grounded.[12] Scientific belief, on the other side, corresponds to the knowledge of the scientific results, together with its acceptance as true, when this acceptance is due to mere belief in the authority of the teacher or of 'the scientists'. Scientific belief is just a modern kind of superstition. However, it is much easier to acquire than scientific knowledge.

One possible way to acquire scientific knowledge, in the above sense, it is to study the history of science[13] – but not 'Whig history'. It is necessary to study the scientific context, the experimental basis, the several alternatives of the time, and the dynamic process of discovery (or invention), justification, discussion, and diffusion. In this way can one learn how a theory was justified and why it was accepted. At the same time, one will learn a lot about the very nature of science.

10. CONCLUSION

Newton's first paper presented an experiment where a beam of solar white light passed through a prism set at minimum deviation position and perpendicularly reached a wall. According to common refraction laws (that is, the Snell-Descartes law), the spot at the wall should be circular – but only a complex theoretical computation can prove it.

Newton found that the spot was oblong. The explanation provided by Newton for this new phenomenon was that white light is a mixture of rays, of different colours, which differ in refrangibility. Newton justified this statement by a smart combination of experiment and theoretical argument.

Newton studied the relation between colour and refrangibility in the *Experimentum Crucis*. He stated that to each colour corresponds a well-defined refrangibility, and conversely. This property only applies to pure or primary colours – those that cannot be decomposed by a prism. This new concept introduced by Newton was central to his argument.

By a set of experiments, he showed that pure coloured light is immutable in several circumstances where composed colour changes. Since pure colours are immutable and since each colour is related to a given refrangibility, this last also must be immutable.

In no experiment with pure or compound colours did Newton observe the change or creation of new colours, or the change of their refrangibility.

Since the refrangibility of the rays is immutable they must be the same before any refraction, that is, prisms do not modify this characteristic of the rays. Hence the coloured rays are already present in white light before it passes through a prism.

To confirm his theory, Newton presented another experiment: the coloured rays emerging from a prism passed through a convergent lens and at its focus white light was produced, with the same characteristics as those of the Sun. Since entities should not be multiplied without necessity, these two white lights – the solar one and the produced by the convergence of the coloured rays – must be accepted to be equal.

Newton's complex argument does not correspond to a mere 'induction' from experiments. If one wants to teach Newton's theory of light, it is necessary to present it as it is: a fine but difficult piece of scientific work that exhibits the complex interplay of theory and experiment.

A correct understanding of the structure and dynamics of science is essential to education. Without such an understanding, many mistakes may easily occur – as happened with Towne.

Towne's paper does not exhibit the structure of Newton's argument. Many of the misunderstandings pointed above may be attributed to the fact that Newton's argument is not as simple and direct as it was supposed to be. Indeed, below the apparent simplicity of Newton's theory there is a deep and complex work. The detailed discussion of Newton's argument seems a nice example of how the history of science may be used in teaching to discuss the complexity of actual scientific work.

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NOTES

[1] The description of this experiment by Newton in his 1672 paper is accompanied by no drawing. The draft reproduced here is from Newton's manuscript *Lectiones opticae* (*circa* 1672): MS. Add. 4002, fol. 3 of the Cambridge University Library, reprinted in Whiteside (1973).

[2] It is not really correct to say that the prism projects an *image* on the wall, although Newton himself uses this expression. When an optical device produces an image of an object, each point of the object corresponds (ideally) to one single point in the image. When a system of lenses produces a real image of a small light source, the light 'rays' converge after passing through the lens and concentrate to form the image. When an image of the Sun is formed with the aid of a converging lens, for instance, it is possible (with suitable magnification) to see in the image the sunspots that may happen to be visible in the Sun's disk. If we use a divergent lens, it will be possible to project upon a surface a round 'image' of the Sun, but it will be impossible to see sunspots. A prism will produce only a *virtual image* of real objects. This virtual image can be seen if one looks towards the object through the prism. Only if we use both a prism and a converging lens, then it will be possible to produce a real image on the wall. In Newton's first experiment, however, we can only talk about the light *spot* – not the *image* – on the wall. By the way: the distinction between 'objective' and 'subjective' experiments stressed by Towne (1993, p. 117) is nothing but the difference between observing the virtual image and the spot projected on the wall. One way is no more 'objective' than the other: in both cases, light is seen with the use of the observer's eyes.

[3] In this article we shall refer to the first experiment described by Newton in his 1672 paper as 'Newton's first experiment'. One should remember, however, that this was not the very first optical experiment made by Newton. It is possible to find a description of his first observations in the notebooks he kept during the period 1664–1665. See McGuirre and Tammy (1983).

[4] Let us remark how difficult it is to obtain the required angular conditions for Newton's experiment. It is necessary that the prism be put in the minimum deviation position and, *at the same time*, the deflected beam must be perpendicular to the wall of the room where the experiment is being done. If the axis of the prism is horizontal and parallel to the wall (as shown in all drawings), the experiment can be performed only on two precise days each

year. Some difficulties of Newton's experiments are discussed by Lohne (1964, pp. 125–139).

[5] Pardies' computation is wrong, although his method seems correct. Re-doing his calculations, one finds that instead of the divergence of 2° 23′ that Pardies obtained for incidences of 30° and 29° 30′, the correct divergence is 1° 40′. For the incidences of 29° 30′ and 29°, the correct divergence is 1° 57′. For the incidences of 29° and 28° 30′ the divergence would be 2° 29′ and for incidence of 28° 30′ and 28′ the divergence would be 4° 17′. So, *in principle* Pardies is correct: it is possible to explain the length of Newton's oblong spot supposing that all rays have the same refractivity. It is remarkable that Newton did not point out Pardies' calculation mistake.

[6] About Newton's modifications of his experiment, see Mamiani (1976, p. 115).

[7] For more information about the optical theory of Grimaldi see Hall (1987).

[8] Newton made constant use of this kind of simplicity arguments in his work. In his *Philosophiae naturalis principia mathematica* one finds a set of philosophical rules (*Regulae philosophandi*). Two of them, that were already found in the first edition of this book, read: 'Rule 1: We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances. Rule 2: Therefore to the same natural effects we must, as far as possible, assign the same causes'. This is a clear presentation of the methodological rule he had already used in his optical work. (See: Koyré 1972, Vol. 2, pp. 550–6).

[9] Notice that this is a strange property of light. In the case of sound, human sensation is able to distinguish pure tones (those corresponding to a single frequency) from compound tones. There is a subjective quality (pitch) that allows us to distinguish between notes of the same main frequency produced by different instruments. When two different notes are played together, they do not produce a single intermediary sound: they are heard separately and can be harmonious or otherwise. There is nothing of this kind in light and colour – but there is no *a priori* reason why light and sound should lead to different sense structures.

[10] Newton's first experiment is usually called 'the experiment of decomposition of white light'. The name itself implies the conclusion.

[11] To understand this possibility, one may compare the phenomena of light to those that occur in chemistry. In some cases, when we join two pure substances it is possible to separate them again by physical procedures (distillation, or another process). However, in other cases, the union of two pure substances produces a third pure substance that cannot be decomposed by physical procedures. It could happen, *in principle*, that something similar occurred to light: in some cases we could have a mere *mixture* of colours, in other cases a *combination* of colours. It could also happen that the result of the combination of colours could not be decomposed by a prism.

[12] This distinction has been pointed out by Rogers (1982), although in a slightly different way – he assumed that scientific knowledge is *true*. Of course, scientific knowledge may be useful, well grounded and acceptable, but it is temporary and not *true*, in a philosophical sense.

[13] Another way is, of course, the practice of scientific research. However, in an educational context, it seems that the only way of acquiring scientific knowledge about 'established' science is the historical one.

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