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Newton's Experimentum Crucis from a Constructivist Point of View

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I, Philipp Kanschik, hereby declare this work to be my own, that I have acknowledged all the sources I have consulted in the paper itself and not only in the bibliography, that all wording unaccompanied by a reference is my own, and that no part of this essay can be found on the internet. I acknowledge that this paper has not been handed in at another university in order to obtain an academic degree.

Signature

1. Introduction: Science and Reality

Being skeptical about reality has become easy. Philosophers of science, amongst others, have taught us in recent decades that we need to pay attention to the contingent circumstances that shape our beliefs about the world. It is now considered naive to think that those beliefs directly reflect matters of fact. Between our thinking and the world is a massive division. Each of us sees the world differently; we live in different environments, have different world views, different characters, different motives and, thus, we see, interpret and think of reality differently. Whatever we hold to be true may only reflect special social and personal circumstances—does the underlying reality have a grip on our beliefs at all?

Science is the mode of human thinking that tends to be considered the most independent of such contingent circumstances. Science is arguably our most reliable body of knowledge. Still, many philosophers use all kinds of theoretical arguments to deny that science can yield certain knowledge about the real world. This paper will not deal with such arguments, but rather take a different stance. If the skeptics are right and even science does not establish truths about reality, then, in principle, one has to be able to find elements of contingency in every scientific theory. For every single theory in science, one must be able to explain its development and success without using realist concepts like rational argument, empirical adequacy or abstract reason. This task, of course, is impossible to actually carry out and that could be the reason why a skeptic may rather choose to stay within the generalist realms of armchair philosophy.

However, it could be a smart strategy for the skeptic to pick out single cases in the history of science, which at first sight clearly seem to confirm the realist. For such a paradigmatic case, the skeptic could then attempt to show how contingent aspects played a crucially important role. One could look for such a case in the hardest of all sciences: physics. And one may decide to choose a case that involves one of the greatest physicists ever and a theory that is still widely accepted today.

Newton's *experimentum crucis* and his 'New Theory about Light and Colors' provide us with such a case. This paper shall examine if one can explain the establishment of Newton's experimental facts without realist assumptions. It will heavily draw on the work of Simon Schaffer, a skeptic constructivist who has published a 36 page-paper about the experimentum crucis (Schaffer 1989).

In Chapter 2, I briefly introduce Schaffer's anti-realist intellectual background and present one of Schaffer's constructivist case studies which depicts a 17th century controversy about air-pump experiments between Robert Boyle and Thomas Hobbes (Shapin & Schaffer 1985). I will examine Newton's experiment with a similar conceptual framework in Chapter 4, and, given several parallels between the Hobbes-Boyle debate and the controversies surrounding Newton's experiment, I will frequently compare the two cases in later chapters.

Chapter 3 is devoted to Newton's letter to Oldenburg from 1672, in which he describes the experimentum crucis and his 'New Theory' for the first time publicly. My analysis highlights the difference between observational facts and theory in Newton's experiment and is sensitive to the question, what Newton intended to prove with the experiment and why.

In Chapter 4, I examine Schaffer's constructivist analysis of Newton's experimentum crucis. His main claim is that Newton could establish the facts and meaning provided by the experimentum crucis only by means of authority. The main reason for this is the controversial character of prisms as an experimental device. I argue that Schaffer overrates their controversial character and that controversies surrounding the experiment were rather caused by Newton's incomplete presentation in his letter to Oldenburg from 1672. Thus, it is implausible to hold that the acceptance of the experiment was achieved by means of authority.

Finally, concluding in Chapter 5, I argue that, compared to Schaffer's analysis, a realist story appears to be more sensible in case of Newton's experiment and his 'New Theory'. Yet, I believe that Schaffer could have done a better job. In a brief outlook, I suggest a few reasonable starting points for further anti-realist analyses.

2. Simon Schaffer's Constructivist Approach

The term 'constructivism' is ambiguous in philosophy of science. The goal of this chapter is not to explore all of its various uses, but concentrate on those which are relevant for the understanding of Simon Schaffer's anti-realist approach concerning Newton's experimentum crucis.[1] After a theoretical section, I outline Schaffer's constructivist case study about the 17th century controversy between Hobbes and Boyle concerning air-pump experiments to illustrate his methodology.

2.1 Realism and Constructivism

Following Godfrey-Smith, I distinguish between social and metaphysical constructivism (2003:181-183). This terminology is somewhat arbitrary and other authors use different terms and categories, but I find Godfrey-Smith's distinction quite useful to clarify Schaffer's position, as shall become more obvious later.

Social constructivism holds that scientific theories are influenced by social forces. Scientists are part of an academic community and the wider society; they have personal relationships, families, friends, enemies, interests, world views, and moral convictions. All these non-scientific aspects affect the work they do in science. While this assertion may appear to be trivial, many philosophers of science used to regard science first of all as a rational enterprise, for which contingent aspects of human existence played no important role. This

1 For example, I will not have anything to say about van Fraasen's influential 'constructive empiricism' (van Fraasen 1980).

view was successfully challenged in the second half of the 20th century, especially by Thomas Kuhn (Kuhn 1962/1996). As a result, in contemporary philosophy of science virtually nobody denies the main claim of social constructivism, namely that social forces do play an influential role in the development of scientific theories.

It is important to realize that social constructivism is compatible with scientific realism. Realism is yet another notoriously ambiguous term in philosophy of science. Cautiously formulated, its main claim may be characterized as follows (Godfrey-Smith 2003:241):

„There is a real world that we all inhabit and that one reasonable goal of science is describing what the world is like."

Being less cautious, a scientific realist may claim that... (Bortolotti 2008:98):

„[...] our current scientific theories are true, and that the theoretical entities and relations they posit truly exist."

For any realist about science, the real world constrains science and via this constraint, scientific theories approach and connect with truths about reality.[2]

Scientific realism is not necessarily incompatible with social constructivism because a realist may believe that social forces affect the development of scientific theories greatly, and yet still hold that those theories somehow successfully reflect certain aspects of the real world. Even though all kinds of social forces influence scientists, they may still be able to uncover truths about reality.[3]

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2 A brief characterization of the different varieties of scientific realism can be found in Nola (1988:3-10).

3 This claim is convincingly defended by David Papineau (see Papineau 1988:37-57). Papineau's argument draws on the distinction between a Cartesian and a naturalist epistemology, of which only the latter is compatible with the anti-realist social constructivist approach from recent decades. The only drawback in Papineau's paper is that he does not distinguish between social and metaphysical constructivism. I believe that his argument only applies to the former.

However, scientific realism is incompatible with metaphysical constructivism. Metaphysical constructivists hold that it is impossible to describe reality as existing independent of thought, because it is thinking that constructs the way we perceive reality (Godfrey-Smith 2003:181).[4] This type of constructivism comes in many different varieties which all share a strong relativism about scientific theories. The important issue for this paper is the kind of metaphysical constructivism that Simon Schaffer uses. This issue is further elaborated in this and the next section. For the moment it suffices to note that if one radically denies the connection of scientific theory to any mind-independent truths about the real world, as metaphysical constructivists do, then one cannot possibly be a realist about science.

The 'strong program' in sociology of science radically denies that connection. This research program can be regarded as Simon Schaffer's intellectual background. It can be traced back to the middle of the last century, with Robert Merton as an early central figure.[5] His research together with Kuhn's influential work set the tone for the so-called 'strong program' in sociology of science. This program transcends traditional sociological investigations and makes ambitious philosophical claims embracing relativism and constructivism.

Instead of outlining the 'strong program' from a theoretical point of view, I rather wish to describe a paradigmatic case-study to illustrate its methodology and objectives. This case-study is particularly enlightening in context of this paper, because it happens to depict a controversy in 17th century England, at a time when Newton was a

4 One could argue that this version of constructivism should rather be called epistemological constructivism, because it may not necessarily deny the existence of an objective reality, but only that human beings have access to it. More radically, one could deny the existence of reality altogether. To avoid confusion, I stick to Godfrey-Smith's terms.

5 Merton focuses on the norms that govern scientific communities and identified universalism, communism (meaning the common ownership of scientific ideas), disinterestedness and organized skepticism as crucial. He also emphasizes the importance of recognition in science (see Merton 1957/1973 and Godfrey-Smith 2003:122-125).

young scholar in Cambridge. It also happens to be mainly concerned with experiments and their credibility. And it happens to be co-authored by Simon Schaffer.

2.2 Leviathan and the Air-Pump

In 'Leviathan and the Air-Pump', Steven Shapin and Simon Schaffer present a constructivist case-study about a controversy between Robert Boyle and Thomas Hobbes in the 1660's and 1670's concerning Boyle's air-pump experiments and the program of experimental philosophy in general. They characterize the stance of their two protagonists as follows (1985:7):

„Boyle appears as the major practitioner of systematic experimentation and one of the most important propagandists for the value of experimental practices in natural philosophy. Hobbes takes the role of Boyle's most vigorous local opponent, seeking to undermine the particular claims and interpretations produced by Boyle's researches and, crucially, mobilizing powerful arguments why the experimental programme could not produce the sort of knowledge Boyle recommended.“

In this controversy, Boyle clearly prevailed and as always, winners seem to write history. Historiographical discussions tend to quickly dismiss Hobbes, if they mention him or any opposition to Boyle's program at all. If mentioned, Hobbes is portrayed as unable to grasp Boyle's experimental approach: he is supposed to have been too ill-qualified in mathematics and physics, too old, too dogmatic, and too ideological (see Shapin & Schaffer 1985:11-12).

Shapin and Schaffer take a different stance. They do not seek to evaluate the controversy in favor of Boyle but to put themselves in a position in which „objections to the experimental programme seem plausible, sensible, and rational“ (1985:13). They aim to show that Hobbes' criticism could have found a different reception in a different intellectual climate. Their goal is not to argue for Hobbes' view but to show that neither Hobbes' nor Boyle's positions were superiorly rational, justified and believable. Boyle's success crucially depended on contingent circumstances.

The analysis of this controversy is based on a metaphysical constructivist premise. Shapin and Schaffer treat truth and objectivity as historical products that emerge from a social struggle. They radically rule out the force of reasonable argument. Using concepts like truth and rationality, they always refer to social constructs rather than mind-independent and impartial forces. The constructivist premise is explicitly assumed without any supporting arguments (1985:15):

„One can either debate the possibility of the sociology of knowledge, or one can get on with the job of doing the thing. We have chose the latter option.“

It is important to highlight this point because Schaffer uses the exact same strategy in his analysis of Newton's experimentum crucis.

Let us move on to the actual case-study. In 1660, Robert Boyle presents 43 experiments that involve the used of a newly constructed air-pump. This air-pump is “big science”, as Shapin and Schaffer write (1985:38). It is not only extremely expensive but also an unprecedented experimental innovation which serves as a showcase piece of the newly founded 'Royal Society' of which Boyle is a member at that time.[6] The experiments address issues in the vacuism-plenism debate from a new perspective. The old debate about the possibility of a vacuum was metaphysical, not empirical and Boyle and his adherents clearly

6 The role of the Royal Society in establishing not only Boyle's experimental program, but also Newton's experimentum crucis, shall become important in later chapters.

recognize this fact. However, Boyle does not see this as a problem because he is not trying to work within the old metaphysical debate. His goal is rather to create a new, empirical discourse with a reformed concept of vacuum (Shapin & Schaffer 1985:46):

„By 'vacuum', Boyle declared, 'I understand not a space, wherein there is no body at all, but such as is either altogether, or almost totally devoid of air.'"

Given this definition, vacuums become accessible with experiments. Of course, Boyle cannot answer the metaphysical questions with empirical investigations. But he believes that these questions are negligible because they can never possibly be settled anyway (Shapin & Schaffer 1985:45-46).[7]

According to Shapin and Schaffer, in order to create this new discourse, Boyle used three technologies to construct and establish experimental facts (1985:25). The 'technology'-metaphor is no coincidence here. Contrary to realism, Shapin and Schaffer do not take facts as something that can be passively observed. The construction of facts is an active process which requires 'technology'.

In case of air-pump experiments, material technology involves the construction and operation of the pump. The literary technology is the means by which the experiments were described to non-witnesses. And the social technology incorporates the conventions that structure the discourse about knowledge claims in the community of experimental philosophers.

The three technologies are closely related. Each one may serve to legitimize the other two. In Boyle's as much as later in Newton's case, Schaffer claims that social technology was crucial to establish a controversial material technology. In Chapter 4, I come back to this

7 It seems that Boyle is a pioneer of an anti-metaphysical, empiricist stance that later became very influential in philosophy and, e.g., was held by the logical empiricists (Carnap 1932/1959).

issue and analyze Newton's experimentum crucis and the establishment of matters of fact in terms of the three technologies.

Concerning material technology in Boyle's experiments, I cannot go into technical details here. The air-pump is supposed to empty a glass globe from air. Unlike with earlier German air-pumps, one can perform experiments in glass globe, e.g. put animals and candles in there (of which the former die shortly after the pumping starts and the latter simply go out). However, there is one important drawback: the pump leaks and can only produce a space which is almost, but not completely devoid of air.[8]

Boyle recognizes the fact that it is difficult to replicate his experiments. There are few, if any air-pumps and the success of replication depends on contingent acts of judgment (Shapin & Scheffer 1985:38-39;225-281). Consequently, virtual witnessing via literary descriptions becomes crucially important. To give the reader a vivid impression of the experimental setting, Boyle uses detailed visual representations. He takes great care of appearing as a reliable witness and experimentalist and thus provides much circumstantial detail to prove his disinterestedness, i.e. by even reporting failing experiments. He uses a plain, functional style, devoid of rhetoric. Whenever he speculates beyond the experimental matters of facts, he sticks to a cautious, probabilistic language.

The establishment of indubitable matters of fact is stipulated by this method; however, a social dimension plays a crucial role. Boyle is a son of the Earl of Cork: undoubtedly, this fact affects his credibility. Furthermore, he describes the witnesses of his experiments as noble

8 This fact is not denied by Boyle. Rather he takes it into account in theorizing about his experiments. For details concerning two main experiments and how leakage plays a role in them, see Shapin & Schaffer 1985:40-49. I cannot devote more space to the content of the experiments and the theories behind them, since the main issue of this paper is not the vacuism-plenism debate.

men.[9] These aspects are important, since the experimental program and its methodology have not achieved hegemony in the 1660's. The community is small, and, despite the existence of the Royal Society, hardly institutionalized. It has many opponents in England and even more on the continent.[10]

All three technologies seek to establish matters of fact: the air-pump produces material matters of fact, Boyle's literary technique serves to create an experimental community to appreciate these facts and his social technology aims to secure knowledge about facts collectively.

For Boyle, there cannot be disagreement about matters of fact but only about theories. Such dissent is aimed to be institutionalized and manageable within the experimental program.

Thomas Hobbes' main critique on Boyle's experiments are his doubts about the manageability and rationality of such an enterprise. For Hobbes, there should be no real difference in certainty between matters of fact and the theories which explain their causes. If one wants to do proper philosophy, one must achieve the highest degree of certainty for both. Such knowledge can be yielded by a proper philosophical method. Hobbes believes that the experimental program lacks such a method, and, therefore, cannot provide any certainty.

There are a number of further aspects that Hobbes criticizes (for a detailed account, see Shapin & Schaffer 1985:110-154). First of all, he insists that not even matters of fact in the experiments are of certainty. He criticizes the restricted public access to the experiments: they are only witnessed by the self-selected clique of experimental philosophers and whoever they judge worthy to be invited. For Hobbes, evaluating

9 The importance of testimony to establish matters of fact is extensively discussed in Shapin 1994.

10 At the time when Newton takes presidency of the Royal Society, things have already changed. In the 1660's, even manners of dispute were yet to be established. For example, Boyle had to insist upon the common-place that disputes should be about findings and not about persons (Shapin & Schaffer 1985:73).

testimony about experiments is as problematic as it is in court or concerning history.

Another strategy by Hobbes is to take the experimental facts for granted, and then show how a different theory, his own, can better account for them than Boyle's. I cannot go into detail here, but only note that Hobbes bases his criticism on the leakage of the air-pump.[11] As we will see later, Hooke uses a similar strategy to criticize Newton's experimentum crucis. He acknowledges the observed phenomena but never changes his opinion that his theory can explain them better than Newton's.

Summing up, observing experiments without being able to infer the causal mechanisms behind them seems useless to Hobbes. Therefore, he believes that experiments can at most be used for illustration, but decisive for reaching consensus are method and theory.[12]

Hobbes was never a member of the Royal Society and never published anything in the Society's journal 'Philosophical Transactions'. Most likely, this was a consequence of his critical attitude towards experiment, but Shapin and Schaffer see the reason for this as much in Hobbes' personality as in his philosophy (1985:139). Boyle was modest and humble, while Hobbes appeared to be confident and intolerant; and both characters exemplified their philosophical program (1985:154).

11 Hobbes claims that all experimental phenomena can best be accounted for by supposing that the glass globe is always full of air. Thus, he rejects Boyle's theoretical explanation for experiments, namely that they are caused by a vacuum. According to Hobbes, the leakage of the air-pump is supposed to create a violent circulatory wind in the globe which causes the death of the animals and puts the candles out; in this manner Hobbes proceeds and explains many of Boyle's observation in terms of his own theory. This argument shows that Hobbes indeed knows the details about the air-pump experiments (although he never witnessed them) and that he is not a priori rejecting experimental findings.

12 The following quote illustrates how devastating Hobbes judges the lack of theoretical certainty for Boyle's program:
"If indeed philosophy were (as it is) the science of causes, in what way did they [the experimental philosophers] have more philosophy, who discovered machines useful for experimentes, not knowing the causes of the experiments, than this man who, not knowing the causes, designed the machines?" (Shapin & Schaffer 1985:142) An experimental philosopher is for Hobbes not more than a craftsman who knows that the thing he produces works, but not why.

We will later see that Newton was more a Hobbesian than a Boylean character.

In this section, I have presented an example of sociology of knowledge in action. Shapin and Schaffer do not focus on the rationality of Boyle and Hobbes but focus on their 'technologies', their style, their personalities and their social environment. They find that all these aspects greatly mattered for the outcome of the controversy, as social constructivism would predict. Metaphysical constructivism is a methodological premise in their program. One may regard the Hobbes-Boyle case study as an attempt to see if one can explain and understand a scientific controversy by denying realistic notions. Shapin and Schaffer conclude that one can explain everything with this method in the given case.

I shall not evaluate this claim. Rather, the Hobbes-Boyle case serves as an illustration of the constructivist method. Furthermore, there are some striking parallels between the Hobbes-Boyle controversy and the controversies about Newton's experimentum crucis, which I shall refer to in later chapters.

3. Facts and Theory in Newton's Letter from 1672

Before turning to Schaffer's constructivist claims in Chapter 4, I examine Newton's letter to Oldenburg from 1672, where he publicly mentions the experimentum crucis for the first time. I seek to demonstrate what counts as a matter of fact and what as theory in the letter. Furthermore, I raise the issue what Newton actually wants to prove with the experimentum crucis—it turns out that this is all but an easy question.

3.1 Facts

On February 6th 1672, Isaac Newton, at that time a young and hardly known scholar in Cambridge, sends a letter concerning his 'New Theory about Light and Colors' to Henry Oldenburg, the secretary of the prestigious Royal Society, which we have already encountered in the Hobbes-Boyle debate. The letter is published in the Society's journal 'Philosophical Transactions'. Newton describes several experiments, amongst them the experimentum crucis, and draws revolutionary theoretical consequences for the science of optics (Newton 1959-1977, 1:92-106).

Newton starts with the description of a basic experiment. In his darkened chamber, he makes a circular hole in his shutters. Then, he puts a prism in front of the hole. By passing the prism, the sunlight is refracted and an oblong spectral diversion of colors appears on the wall. Newton is surprised by the oblong form because the hole is circular. He wonders how this fact relates to the diversity of colors on the wall.

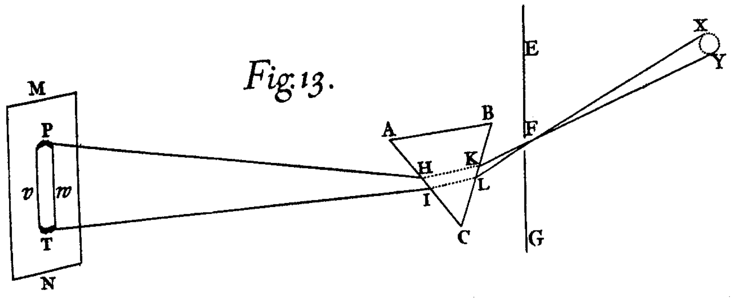

Fig. 1: Newton's basic experiment demonstrating the elongated spectrum. The image is taken from Newton's Opticks, Book 1, Part 1, Proposition 2, Experiment 3 (1704/1979:27).

In an attempt to explain this observation, Newton takes two boards with small holes and places them 12 feet apart from each other for the experimentum crucis. Then, he places one prism in front of the first board and one behind the second board. After the sunlight passes the first prism, only a small portion of the refracted light is transmitted through the first board. An even smaller portion passes the hole of the second board, before being refracted by the second prism. By rotating the first prism, the experiment allows to single out different portions of light from the elongated spectrum.

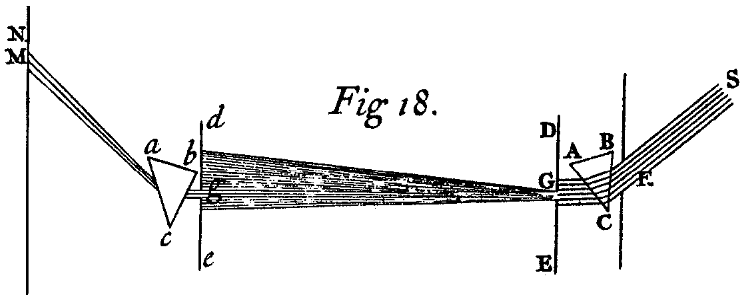

Fig. 2: The experimentum crucis. The image is taken from Newton's

Opticks, Book 1, Part 1, Proposition 2, Experiment 6 (1704/1979:47).

For Newton, the basic experimental observation turns out to be that the portion of light which is refracted to the greatest extent by the first prism, is also refracted to the greatest extend by the second prism. Analogously, portions of light that are reflected less by the first prism are also refracted less by the second prism. Even though the two boards guarantee an equal incidence of all incoming rays, each portion of light from the oblong spectrum is refracted differently by the second prism, in accordance with its degree of refraction by the first prism. Furthermore, there is no elongated, but always a circular image after the second refraction. Thus, it seems that the rays that pass the second prism behave totally different than the unrefracted sunlight that enters the first prism.

It is important to note that Newton does not mention colors in his description of the experimentum crucis. Later on, Newton often held that his theoretical claims about refrangibility and colors were independent, with only the first being proven by the experimentum crucis. Still, it is easy to understand why most of Newton's contemporaries treated the experimentum crucis mainly in terms of color theory. The facts in the experimentum crucis include some interesting observations of colors. Some rays that pass the second prism appear to have so-called primary or original colors. This means that they do not change their color after the second refraction. The rays that are refracted the most by the first prism, turn out to be violet; the least refracted are red and in between is the whole spectrum of colors. Other portions of light do change their color again to some extent after the second refraction and, thus, do not have original, but compound colors. By mixing different rays from the spectrum, one can produce colors that look like original colors, but it is always possible to decompose these colors by refraction.

To sum it up, observational facts in the experimentum crucis are:

depending on how much a portion of light is refracted by the first prism, it will show the same degree of refraction after passing the second prism; after the second refraction, there is no longer an elongated but a more or less circular image; and some portions of light appear to not change their color again after the second refraction.

3.2 Theory

From these observations, Newton deduces his theory. He emphasizes that his theory is not just another speculation trying to explain experimental observations. Rather, he sees his conclusions as “not an Hypothesis but most rigid consequence, not conjectured... but evinced by the mediation of experiments concluding directly and without any suspicion of doubt” (Newton 1959-1977, 1:96-97).[13] This certainty is provided by the 'experimentum crucis'.[14]

There are two main theoretical claims in Newton's letter: Light consists of rays of different refrangibility and there is a one-to-one correspondence between refrangibility and original colors.[15]

Concerning refrangibility, Newton believes to have ruled out

13 The paragraph affirming this conviction was not included in the published version of his letter to Oldenburg, most likely because Oldenburg thought that it was outrageously contentious (see Shapiro 1996:67 and Sepper 1994:35;37).

14 Note that Newton's methodology is contrary to the methodology of Boyle and the Royal Society. However, if successful, Newton's 'New Theory' satisfies Hobbes' demands concerning certainty . I will come back to this issue in section 4.4.

15 Thus, with 'unequal refrangibility' and 'color immutability', one could refer to observational facts as much as to theoretical claims. Unless indicated otherwise, I shall always use these terms to refer to observational facts for the rest of this paper. I realize that it is problematic to divide so strictly between facts and theory. After all, can one plausibly speak of 'original colors' and 'refrangibility' without any theoretical background? I concede that in a strict sense, this may be impossible. Yet, I believe that it is comprehensive for the given case. When somebody like Robert Hooke accepts observational facts in the experimentum crucis but rejects Newton's theory, we have no trouble to make sense of his position. I find that the fact / theory distinction provides a sensible framework for the analysis of Newton's experiment. However, this does not mean that I believe one can perfectly divide facts and theory.

'modificationist' theories of light.[16] These theories treat white light as the basic homogeneous entity which can take different qualitative appearances after interacting with matter, but essentially stays the same. Thus, for a modificationist, devices like prisms only 'modify' the sunlight. For all modificationist theories, colored rays are the result of a modification of simple white light. The experimentum crucis is supposed to falsify the claim that white light is a homogeneous unity which essentially stays the same after refraction and is only modified and transformed in his qualitative appearance. Rather, one must conclude that (white) light is composed of divers rays with different refrangibility.

Concerning colors, Newton simply lays down his doctrine in the second part of his letter. This doctrine states, amongst other claims, that differences in refrangibility correspond to differences in color. A ray of a certain refrangibility shows a certain color, if singled out properly. With his doctrine, Newton deconstructs modificationist theories that treat colors produced by refraction as 'appararent' colors, which are only secondary to the 'real' colors of bodies. Newton inverts this hierarchy and thinks that the so-called 'apparent' colors created by refraction are fundamental, and the so-called 'real' colors turn out to be the disposition of bodies to reflect a certain kind of ray more or less abundantly (Sepper 1994:46 and Schaffer 1989:74).

3.3 What Does the Experimentum Crucis Prove?

On numerous occasions, Newton held that the experimentum crucis is only supposed to prove unequal refrangibility, but as Schaffer notes,

16 Proponents of modificationism include Aristotle, Descartes, Hooke and Goethe (see Zemplen 2005, ch. 8 and Nakajima 1984). The diversity among these theories is so vast that one could deny if modificationism is a sensible umbrella term at all.

Newton was not always consistent. In a public answer to Hooke in June 1672, he said that the experimentum crucis demonstrates that „rays of divers colours considered apart do at equall incidences suffer unequall refractions“ (Newton 1959-1977, 1:187). I agree with Sepper that a complete separation of the two issues is impossible (Sepper 1994:40):

„The light of the least-refracted parts of the first spectrum is least refracted in the second refraction, ..., but if the color of the light changed significantly it would be hard to argue that one had isolated rays with an unvarying property or a unique identity.“

Therefore, it is not a coincidence that Newton connected the two issues in his letter with his 'New Theory about Light *and* Colors'. And nearly all of his readers took the experimentum crucis as aiming to prove both claims. Why then did Newton repeatedly insist that it only proves unequal refrangibility? What reason did he have to limit the scope of his experiment?

I believe that the reason for this goes back to his experiences in the optical lectures he held in 1670-71. As his earlier manuscripts from 1666 show, Newton believed that the experiment proves unequal refrangibility *and* color immutability after his original trials (Schaffer 1989:78). However, in his lectures, he had trouble demonstrating color immutability. If the second prism was placed transverse to the first, there was no change in color, but if it was placed parallel, red rays displayed elements of yellow after the second refraction. Newton conceded that the experimentum crucis “is not yet perfect in all respects” (Schaffer 1989:83). He concluded that it takes more refractions than two to create purer original colors. Furthermore, he discovered that other experimental settings including smaller holes, lenses and a triangular slit even work better (Shapiro 1996:109).[17] Fig. 3 depicts the oblong spectrum from the basic experiment and shows

17 The experiment which Newton uses in the 'Opticks' to prove color immutability, can be found in the Appendix, Fig. 4.

why producing original colors by prismatic refraction alone is difficult.

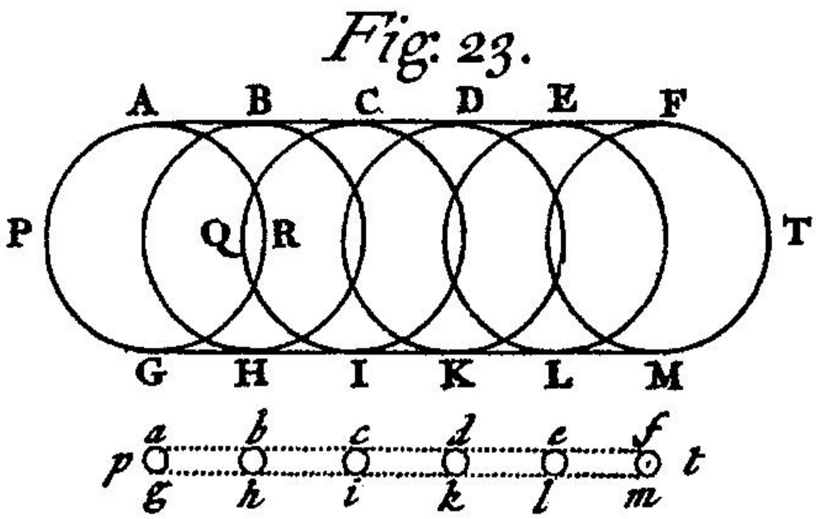

Fig. 3: Color immutability. In Book 1, Part 1, Proposition 4 of the 'Opticks', Newton uses this figure to explain and illustrate a difficulty in demonstrating color immutability (1704/1979:65).

Homogeneous rays with original colors overlap; the separation is only perfect on the edges of the image (A to F and G to M). To achieve a better separation, one has to diminish the diameter by making the hole in the wall smaller. But these separations remain imperfect. There are better experiments to produce original colors. Only, in the 'Opticks', Newton explains the shortcomings of prism refraction. Before 1704, he never gave a public account of these trials and methods, even though his optical lectures show that he had already developed them.

Thus, Newton had good reasons to eliminate colors from his description of the experimentum crucis. But one may wonder why he did not include any experiments proving color immutability. Maybe, the initial queries after his letter discouraged Newton to publish further optical papers. Maybe, he was saving the proof of color immutability for a major optical treatise, which, for various reasons, took him another 32 years to publish.

Fact is that the letter from 1672 remained his only publication in optics for a long time and that, hence, crucially important information was not available for the following 32 years.[18] Most of his readers, including critics and adherents, believed that the experimentum crucis is supposed to prove color immutability and almost all controversies surrounded this issue.[19] Newton confirmed this misunderstanding implicitly and explicitly several times, instead of laying all his cards on the table. Interestingly, over the years, numerous experimental philosophers replicated the experiment and believed that it succeeded to demonstrate color immutability. I shall have more to say about this in the next chapter.

18 In 1675, Newton submits two papers on optics to the Royal Society, but he does not allow publication. The first paper deals with the color of thin plates, the second is a speculative piece about the nature of light (Shapiro 2008:423-24).

19 Up until today, the misinterpretation of the experimentum crucis seems to have survived. See Appendix, fig. 5 for an illustration from a modern German physics textbook, which resembles the experimentum crucis and is supposed to demonstrate color immutability.

4. Newton's Experimentum Crucis from a Constructivist Point of View

Newton's experimentum crucis is a paradigmatic case for realists. For a constructivist like Schaffer, there is a lot to win by deconstructing its rationality. And indeed, there are many possibilities for a constructivist approach to the experiment, too many to tackle here. My analysis mainly concentrates on one aspect, namely the question how Newton's experiment could produce and establish matters of fact. Schaffer himself concentrates on issues like experimental technology, replication, mode of presentation and authority. He neglects the question how Newton could plausibly infer his theory from the observed matters of fact. In what follows, I will only occasionally deal with theoretical issues; otherwise, I stick to Schaffer's points.

I believe that Schaffer's strategy is particularly interesting because, being already within a realist's terrain, he chooses the most difficult aspect for his attack. I believe that it is much easier to show that Newton's 'New Theory' does not naturally follow from experimental facts, that other theories were compatible with Newton's experiments as well, and that one can nowadays still make sensible objections to Newtonian optics. However, to argue that even matters of fact in the experiment crucis are 'constructed' and, hence, contingent, is a much more difficult claim to defend.

4.1 Evaluating Experimental Matters of Fact

In 1672, Newton's 'New Theory about Light and Colors' was initially received with much enthusiasm, but soon criticized on various grounds.

Some of this criticism related to prisms and the unclear presentation in the letter. Others did not concern matters of fact but theory.

Simon Schaffer thinks that the former were the main cause of the controversies surrounding the experimentum crucis. He does not believe that the clearer and more transparent accounts of the experimentum crucis in Newton's correspondence and in the 'Opticks' were decisive to establish matters of fact. Rather, he claims (Schaffer 1989:67):

“The acceptance of a matter of fact on the basis of an experimental report involves conceding authority to the reporter and to the instruments used in the experiment.”

Authority is the key term in this quote. In 1672, Newton had no authority over the social institutions of the experimental community and neither was there an optical discourse in which Newton's experiment and theory were easy to incorporate. According to Schaffer, the universal acceptance that Newton's theory achieved in the decades after the publication of the 'Opticks' was due to the overwhelming authority in the experimental community that he had gained by then (Schaffer 1989:100). With this influence, he could define the discourse in his own terms and secure matters of fact.

Schaffer claims that Newton was able to achieve closure in the first decades of the 18th century. Closure is established after a social struggle and links instruments to matters of fact. After closure, experimental instruments become transparent as “uncontestable transmitters of messages from nature” (Schaffer 1989:70). Once this transparency is achieved, it is hard to recapture the contingent and controversial character that instruments like prisms initially had. Again, Schaffer believes that there is nothing natural in the link between an experimental device and a matter of fact. Rather, closure is a social process. After closure, scientific developments seem to sustain a realist history, and only by critical historical analysis, one may uncover their contingency (Schaffer 1989:70-71).[20]

Can Schaffer support his far-fledged claims with historical evidence? This chapter will be concerned with the question, how and if Newton's experiment could provide matters of fact. The analysis will be based on the distinction between material, literary and social technology that Shapin and Schaffer use in “Leviathan and the Air-Pump” (see section 2.2).

Material technology involves the analysis of prisms as an experimental device. In discussing literary technology, the shortcomings of Newton's description of the experimentum crucis will be stressed. And concerning social technology, I evaluate Newton's authority to decisively establish experimental matters of fact.

4.2 Material Technology: Prisms as an Experimental Instrument

Simon Schaffer believes that the status and meaning of the experimentum crucis in the 1670's was hard to fix. An important reason for this was the lack of an agreed criterion for good prisms. At Newton's time, prisms were not regarded as a standard experimental device. Schaffer suggests that they were more often regarded as entertaining toys that could produce charming colors (1989:74). Still, well-known natural philosophers like Descartes, Hooke and Boyle had in recent decades begun to use prisms for optical experiments. Boyle's claim that prisms are “the usefullest Instrument Men have yet imploy'd

20 As in 'Leviathan and the Air-Pump', Schaffer is making philosophical claims and assumptions but avoids theoretical arguments. He does not even make explicit that his paper on Newton is based on a sociology-of-knowledge or constructivist approach. However, I believe that it is safe to assume this and analyze his paper as such.

about the Contemplation of Colours” may have encouraged Newton to start experimenting with prisms (Schaffer 1989:76).

Compared to Boyle's air-pump, prisms had the advantage that, in principle, anybody could buy them and replicate Newton's experiment. Thus, unlike Boyle, Newton was not so much relying on virtual witnessing. But he faced another problem: prisms in the 17th century were of different quality and design. Some were tinged with color, others were vitiated with bubbles and veins. The prisms also had different angles. Newton acknowledged that one could not reproduce the experiment with all prisms; with some prisms they did not work.

Schaffer stresses this point and makes it the basic foothold of his constructivist analysis. According to him, prisms were not a natural experimental devices to produce incontestable matters of fact. Rather, their use was highly contingent: it was unclear what a good prism is, how to use it in an experiment, and what kind of knowledge claims it can support. Only after one had established such standards, prisms could be used to yield knowledge. According to Schaffer, it was not scientific rationality, but authority, that lead to such establishment.

To illustrate the problems with prism quality, Schaffer highlights Newton's correspondence with Anthony Lucas and the Jesuit group in Liège, where Newton repeatedly attributes their failure to reproduce the experimentum crucis, and even the basic experiment with the elongated image, to the supposable inferior quality of their prisms (Schaffer 1989:90). However, one can question the importance of this case. According to Shapiro, the Jesuits from Liège were isolated and without credibility within the scientific community; therefore, one may regard their failure as relatively unimportant (1996:78).[21]

Indeed, the Royal Society and various other natural philosophers succeeded in reproducing Newton's experiment without having any

21 Apparently, the Jesuits had discredited themselves in England with their opposition to Boyle's air-pump experiments on Aristotelian grounds (Shapiro 1996:78n19).

troubles with their prisms (see Appendix, table 1). But I find it too easy to just point to the low scientific credibility of the Liège group. As Newton in his optical lectures, the Jesuits failed to produce original colors. Even after an explicit demand by Lucas, Newton would not reveal better methods (Shapiro 1996:77n16). I cannot judge whether the Jesuit's failure was due to their bad prisms or their experimental incompetence. But rather than regarding them as dilettantes, one could also hold that they were committed to stricter scientific standards than some followers of Newton who believed to have observed original colors with the experimentum crucis.

As a matter of fact, prisms from England tended to work. The origin of the myth that one could only carry out Newton's experiments with English, and not with Venetian prisms, did not originate in the 17th century, but decades later in context of a challenge of Newton's theory by Rizzetti in the 1720's. Schaffer again heavily stresses this point in order to show how Newton had to invoke power to make people use the right prisms. In the very beginning of his paper, he quotes a well-known Italian introduction to Newton's philosophy by Francesco Algarotti from 1737 (1989:67):

“Perhaps, said the Marchioness, Nature has reserved the Merit of demonstrating Truth to the English prisms; that is, to those by whose means she at first discovered herself.”

This ironic quote exemplifies Schaffer's constructivism. Newton, by that time president of the prestigious Royal Society and with disciples all over Europe, could define that prisms which confirmed his theory were proper prisms, while any other prisms were declared to be defect.

However, as Shapiro correctly points out, there is a real problem that lead to failure of the experiment with Venetian prisms. Glass prisms from Venice tended to be full of bubbles and veins and those irregularities inhibited the production of original color by scattering further light into the separated rays. Algarotti himself shows that with prisms (from Britain, as it happens) without such irregularities, Newton's experiments work fine, while they fail with the Venetian ones. Surely, Newton's theory can explain why (Shapiro 1996:127).[22]

Even more important, a detailed description of the proper methods for producing original colors had been available for two decades in the 1720's. In 1714, Newton's disciple Desaguliers had carried out a series of experiments in front of continental philosophers, that were based on the optical lectures and the 'Opticks'. These trials were repeated successfully several times in the 1720's (see Appendix, table 3). In these trials, the experimentum crucis only proves unequal refrangibility, and there are better experiments to show color immutability (Shapiro 1996:112-119, Appendix, fig. 4).

Still, Rizzetti stayed within the old discourse. He placed the two prisms close to each other and used rather large holes (Schaffer 1989:98). It should neither surprise Newton, nor any careful reader of the Opticks, nor anybody who had seen Desaguliers' trials, that this experimental setting cannot produce original colors. I agree with Shapiro that Desaguliers' trials and their replications seem to have established a scientific consensus in the 1720's, and that Rizzetti's critique hence no longer had to be taken seriously (Shapiro 1996:126). Whether or not Rizzetti's prisms were of insufficient quality to carry out Newton's experiments, I cannot decide here, but it does not seem to matter much.

Given that the Jesuits and Rizzetti were the only ones to allegedly fail due to prism irregularities, and given that for numerous replications

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22 In fact, Algarotti made the myth about English and Venetian prisms well known by caricaturing it. Schaffer should have cited the two sentences that follow right after the one he quotes (Shapiro 1996:127-128):
"It would be a very curious Phaenomenon, answered I, to observe such a Partiality in Nature, as for her to prefer such a Prism made in London to one produced in Murano. But the truth is, that if we consult her as we ought, she always answers the same, whether the Prism be English or Italian, provided it be good and well worked;..." Schaffer, of course, would hold that only by authority, one can establish what "good and well worked" means.

this issue did not arise, I believe that it is safe to affirm that prisms are a relatively simple experimental devices, especially if compared to Boyle's air-pump. Concerning the pump, one could not even be sure if it was devoid of air or not, and furthermore, there was only limited access to observation. None of this seems to be true in case of prisms. Thus, I believe that Schaffer exaggerates their opaqueness. The fact that not all prisms could produce the facts that supported Newton's theory is not of great importance. If there are prisms that could provide such challenging matters of fact, then any optical theory needs to explain their existence.

4.3 Literary Technology: Newton's Overconfidence

Despite the fact that Newton did not mean the experimentum crucis to prove color immutability, the crucial issue in its reception was the production of rays with original colors. For Newton's critics, there was a troubling circularity in Newton's experiment that Collins calls the “experimenter's regress” (Collins 1985:79-100, Schaffer 1989:69-70). If an experimenter fails to produce original colors, Newton can always answer that this does not falsify his doctrine, because it only shows the experimenter's incompetence. Therefore, Newton's doctrine appears to be impossible to falsify. As we have seen, Lucas and the Liège group, and later Rizzetti, could not produce original colors; the well-known French experimental philosopher Edmé Mariotte failed, too, as we shall see in this section.

To escape this regress, Newton had to be more explicit about the meaning of the experimentum crucis and the production of original colors. In his letter to Oldenburg, Newton devotes only a single paragraph to the experimentum crucis. His tone is overconfident; he writes like somebody who is without any doubt about the truth of his theory and, thus, does not need to explain every detail. There was not even an illustrating figure of the experimentum crucis. Shapiro may be right in claiming that none of the letter's readers initially understood the dense short description of the experiment properly (1996:74). This marks a stark contrast to Boyle's transparent and illustrative literary technology. Newton builds his doctrine of colors on the existence of rays with original color, but leaves the reader alone with the question of how to achieve “a perfecter separation of the Colours” (Newton 1959-1977, 1:102).

The shortcomings of his letter caused Newton to write countless letters explaining details about the experimentum crucis; a fact that annoyed him greatly. Concerning color immutability, Newton was inconsistent. Several times, he held that the experimentum crucis was not to prove color immutability, but never explained why.[23]

In his biography of Newton, Richard Westfall explains that Newton's overconfidence was due to the fact that his 'New Theory about Light and Colors' had been familiar and natural to him for long in 1672. In 1666, he had already started to experiment with prisms and developed a basic outline of his theory. By 1670, he had carried out all his main optical experiments, and believed to have settled all their relevant implications (Westfall 1996:104-108). Westfall argues that Newton's creative work in optics was complete in 1670 and that optics never received his unlimited attention again, except for working on the illustration of his theory (1996:108).[24] When Newton presented his theory in his letter to Oldenburg, he expected nothing but immediate success. Thus, his correspondence with Lucas and others is

23 Only sometimes, Newton gave specifications about the experimental setting in his letters. He informed the Jesuits and others, how big the hole in the wall is supposed to be, that the experiment works best on a sunny day, that the prism should have an angle of about 60 to 65 degrees, straight sides and that they have to be placed at minimum deviation (Schaffer 1989:88;94).

24 This claim is in accordance with the fact that, when Newton finally published his 'Opticks' more than thirty years later, large parts of his theory had hardly changed compared to his 'New Theory about Light and Colors' and the optical lectures.

characterized by the great impatience of a man who feels as if he repeatedly has to explain that one and one equals two. Newton moved on to new topics, and was yet still pestered with old questions.[25] Obviously, he could not put himself too well in the position of his critics, who were lacking information and clarity.[26]

What Boyle had achieved with the vacuism-plenism debate, Newton wanted to do with the optics. He aimed to shift the discourse about light and colors away from the old modificationist framework by introducing new concepts like 'differently refrangible rays', 'original', and 'compound' colors. Once his conceptual framework is accepted, his theory follows more naturally.

But unlike in Boyle's case, Newton's suboptimal use of literary technology made the establishment of the experimental matters of fact more difficult; a transparent, well thought through account could have greatly reduced controversy. Only in 1704, Newton provided such an account publicly. In his 'Opticks', Newton gave a clear description on how to produce rays of original colors.

Still, even before 1704, his experiment was successfully tested and gaining adherents, amongst mathematical scientists and Scottish natural philosophers (Shapiro 1996:81-88, see also Appendix, table 1). It is unclear to what extend and to what standards they carried the experiment out, but presumably not to Newton's. All we know is that they quickly became convinced of Newton's theory, most likely due to

25 Apparently, setting physics and mathematics aside, Newton devoted much of his research capacities in the 1670's to alchemy. From a contemporary point of view, it is difficult to comprehend why one of the founding fathers of modern science has written over a million words on a seemingly obscure and irrational subject outside of the realm of proper science (White 1997:4). Westfall argues that Newton's interest for alchemy was a rebellion against mechanistic thinking (1996:158), while White claims that Newton's alchemist studies were the key to his revolutionary discoveries in science (1997:5).

26 The necessity to further explain and defend claims which were all obvious to him, caused a personal crisis for Newton and eventually caused him to withdraw from most of his correspondences and return to a more solitary life (Westfall 1996:120). In 1678, he ends the correspondence with Lucas violently and with personal accusations (Westfall 1996:146).

their enthusiasm about Newton's experimental and mathematical approach to natural philosophy.

In contrast to this, Edmé Mariotte, France's leading experimental scientist at that time, conducted a critical test of Newton's doctrine and failed (Shapiro 1996:78). His experiment was not an exact replication of the original experimentum crucis. Since Newton had not yet publicly given a clear account on how to produce rays of original color, experimentators like Mariotte had to find their own method. Using only one board, Mariotte failed to produce original colors.

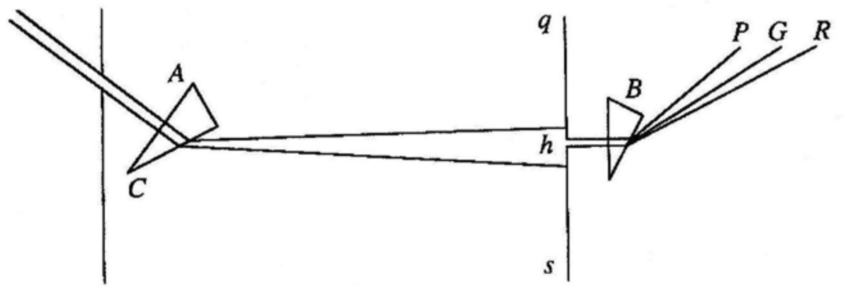

Fig. 6: Mariotte's version of the experimentum crucis.
The image is taken from Shapiro 1996:79.

Due to Mariotte's reputation in continental Europe, this failure turned out to be very influential there. But again, despite the experimenter's regress, it seems legitimate for Newton to insist that this observation does not falsify his theory. For Mariotte's experimental setting, Newton would not expect to observe rays of original color (Shapiro 1996:79-80). It is safe to assume, that Mariotte would have not failed, if he had had access to the optical lectures or the 'Opticks'.

But it is important to note that even Newton's most persistent critics like the Jesuits and Mariotte apparently had no problems with acknowledging unequal refrangibility. The basic elongated spectrum and different refraction of divers rays as experimental facts never seems to have been challenged or problematic to replicate (except by the Jesuits, but only initially): a noteworthy aspect that Schaffer fails to mention.[27] The shortcomings of Newton's letter to Oldenburg certainly delayed the acceptance of the experimentum crucis and obscured the issue of color immutability. However, I do not see a problem for realists here. Rather, I find it stunning that so many natural philosophers, including Hooke and the Royal Society, accepted color immutability as a fact before the 'Opticks', while Newton himself had not yet published anything that would count as a decisive proof of this fact by his own standards.[28]

4.4 Social Technology: Newton's Authority

Let us start this section with a brief overview of some facts concerning Newton's role in the community of experimental philosophers. In 1672, Newton was a young scholar in Cambridge. On the continent, he was unknown, but in England, he had recently made himself a name with his self-made telescope (Westfall 1996:114-117). In January 1672, one month before he wrote the letter to Oldenburg, he was elected as a member of the Royal Society. Within the Royal Society, Newton's methodology was not shared. England's leading authority in optics, Robert Hooke, rejected Newton's theory. One cannot say that Newton's 'New Theory' gained acceptance within the Royal Society. On the continent hardly anyone even knew of it at all.

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27 Of course, the acceptance of the experimental matter of fact did not mean that Newton's critics accepted the theory that white light consists of rays of different refrangibility.

28 Hooke replicated the experimentum crucis and held that it indeed shows that colored rays sometimes maintain a fixed refrangibility: thus, he acknowledged color immutability. But Hooke believed that the matters of fact in the experimentum crucis did not prove any of Newton's theoretical claims. He thought that he was able to account best for them with his modificationist theory and never changed his opinion in the following decades.

That only changed in 1704, when Newton had become president of the Royal Society, and as the author of the widely acclaimed 'Principia mathematica' from 1687, was considered to be one of the leading natural philosophers of Europe. From the chair of his presidency, he presented his 'Opticks'. Hooke, his most influential antagonist, had died a year earlier.[29] Westfall judges Newton's presidency of the Royal Society as despotic (1996:330;338-339); accordingly, he calls the dominance of Newton's theory in the 18th century “dictatorial” (1996:316). Feingold holds that Newton expected members of the Society to “uphold the president's exacting perception of the hierarchy of knowledge” (2001:95). In any case, the Opticks had a strong impact and gained followers everywhere in Europe. In the 1720's, a consensus in the philosophical community on the truth of Newton's theory was forming (Shapiro 1996:126).

Now, here is the story that Schaffer constructs from these facts: in 1672, the young Newton was without power to push his ideas to acceptance. Most importantly, closure and transparency about prisms as experimental instruments could not be achieved, as Newton had no means to silence his critics like Lucas and the Liège group. His lack of power led to an inability to fix the matters of fact produced by the experimentum crucis and other experiments. 30 years later, the situation was all different (Schaffer 1989:92):

“As Newton took power over the key resources of experimental philosophy, Newtonian optics acquired a disciplinary history and a standardised technology.”

By then, Newton was powerful enough to rewrite the history of optics and achieve closure and transparency for his prisms. It was neither the scientific superiority of his account, nor the evidential character of

29 It is often argued that Newton waited until Hooke's death to publish the 'Opticks', because he feared another dispute with him. However, Shapiro argues that problems with the phenomenon of diffraction lead Newton to delay the publication (Shapiro 2008:435).

matters of fact in the experimentum crucis, that led to success. Rather, truth had emerged after a social struggle. Crucial for Schaffer's analysis is not only Newton's role in the Royal Society, but also how he used it in optical controversies.

What was Newton's role in the Royal Society? The Society was founded in 1660, advocating to seek “knowledge of natural things and useful Arts by Experiment” (Feingold 2001:79). The Society's experimental empiricism followed the Baconian tradition (Hall 1991:9-10). Boyle and Hooke were dominating figures and they advocated a “'naive' empiricism and utilitarianism, joined with the incessant rebuke of theory, [...] fortified by the proscription against mathematics” (Feingold 2001:80). Boyle's air-pump experiments were a paradigmatic example. Boyle avoided metaphysical speculation and expressed certainty only about matters of fact, while being very cautious with everything else. Theories always had to be supported by numerous experiments and were treated as 'hypotheses'.

This methodology, of course, was completely at odds with the one that Newton expressed in his letter to Oldenburg. I have already pointed out the difference in literary technology in the last section, but they also greatly differed in method: where Boyle uses many experiments, Newton thinks that one suffices; where Boyle cautiously infers hypotheses from observation, Newton declares not to work with “an Hypothesis but most rigid consequence [...] without any suspicion of doubt”. Boyle was working with a naturalist-inductive approach, while Newton's approach was mathematical-deductive. In 1672, Newton's views were as difficult to reconcile with Boyle's and the Royal Society's methodology as Hobbes' views were some years before.

But all these aspects do not concern matters of fact. The observed facts in the experimentum crucis, even concerning colors, were quickly accepted in the Royal Society, even by Hooke (Schaffer 1989:86-87). Neglecting controversies about theory here, we only need to note that

Newton did not need any power to establish the matters of fact of the experimentum crucis in the Royal Society, even though they tended to have very different methodological and theoretical commitments than Newton. I wonder why Schaffer is not puzzled by this, because Newton essentially faces the same problem as Hobbes, but prevails at least in some respects.

The experimentum crucis only became widely known on the continent after the publication of the 'Opticks'.[30] Again, unequal refrangibility was soon almost universally recognized, while the acceptance of original colors took a little longer. But the intellectual climate at the beginning of the 18th century played in Newton's hands. Mathematical approaches to natural philosophy gained more and more adherents in England and on the continent and no other optical theory could be formalized as neatly as Newton's. In the Royal Society, the old Boylean tradition had lost its power to the Newtonian party (Feingold 2001:91). Even after the 'Opticks', many experimental philosophers continued to interpret the experimentum crucis in terms of unequal refrangibility and color immutability and, unlike in the decades before the 'Opticks', there were only confirmations (see Appendix, table 2). Many philosophers may have joined Newton's program uncritically at that time and, thus, it is plausible to hold that social factor played an important role for the reception of Newton's theory.

But this only confirms social constructivism, and Schaffer aims at something stronger. He claims that dominance on the continent could only be achieved by a Newtonian 'campaign' in 1714, launched by Newton's disciple Desaguliers. This 'campaign' consisted in the demonstration of nine experiments in front of several continental scientists from France and Germany at the Royal Society in London (Shapiro 1996:112-119). It was accompanied by a clear description on

30 Note that Newton does not call it 'experimentum crucis' anymore in the 'Opticks'. Still, he continues to present it as the decisive proof for his claim that white light consists of rays of different refrangibility.

how to conduct them, more or less taken from Newton's 'Opticks' and the optical lectures. Nowhere was history rewritten or insisted on the use of English glass. Rather, the experiments demonstrated how to produce original colors and explained why Mariotte had failed. In the following years, there were many successful replications of the experiments (see Appendix, table 3). For the continent even more than for England, it seems absurd to explain the acceptance of matters of fact merely in terms of Newton's power.

5. Conclusion and Outlook: What Schaffer Should Have Done

At this point, the question arises if Schaffer's analysis succeeds. Is it possible to explain the establishment of matters of fact in the experimentum crucis only by referring to technology and authority, without any realistic notions? I believe that Schaffer's account fails. It seems quite artificial to assert that matters of fact in the experimentum crucis were 'constructed' in the strong sense of metaphysical constructivism.

Certainly, it is less plausible to maintain this assertion than for Boyle's air-pump experiments. Boyle's highly complicated air-pump leaked, and one could plausibly doubt, if it actually created a vacuum or not. This shortcoming was compensated by a smart and well-thought through literary technique and Boyle's distinguished role in English natural philosophy.

A similar argument cannot be run for Newton's case. Newton's experimentum crucis was not easy to carry out, but it provided facts which could be observed much less problematically. He was not making competent use of literary and social technology at all and still gained followers. Matters of fact in his experiment were accepted by people that neither shared his methodology nor his theoretical convictions. The controversy with the Jesuits and Mariotte's failure were due to Newton's unwillingness to publish clarifying information, and Schaffer overrates the problem of prism quality. After the publication of the 'Opticks' and Desaguliers' trial, there was no opposition on the continent (except Rizzetti), but only numerous confirmations, in places where Newton had little power.

Thus, is the experimentum crucis a dream case for realists? Not necessarily. I believe that Schaffer could have conducted a much more powerful constructivist analysis. I want to finish this paper with a brief outlook on what he could have done.

Concerning matters of fact, I believe that the most surprising aspect of the experimentum crucis and its aftermath is the large number of philosophers who replicated it and observed color immutability, even after the 'Opticks' (see Appendix, table 1 and 2). Adherents of mathematical science and experimental philosophy readily seem to have embraced the 'New Theory' without a thorough investigation. A constructivist could focus on this issue and reveal ideological preoccupation.

Yet, I believe that it is more promising for a constructivist analysis to concentrate on Newton's theory than on matters of fact. Newton believed that his theory follows directly from observational facts. He also believed that one experiment suffices to prove far-fledged theoretical claims. Such methodology seems quite odd to the modern reader and can be legitimately questioned. Newton's critics like Hooke and Lucas were proposing alternative experiments and alternative theories, which I have not considered in this paper. A constructivist could examine those theories and demonstrate their plausibility.

The starting point of any analysis arguing for metaphysical constructivism would have to be some kind of flaw in Newton's theory, that opens up the possibility of proposing reasonable alternatives.[31] It is beyond the scope of this outlook to elaborate such alternatives, but I briefly want to point to an obvious problem with Newton's theory which may serve as a promising starting point for such an analysis. Newton believed in the strict correlation of a ray's refrangibility and its color. But the connection between optics and color theory seems to be not as strict as Newton held, because it ignores physiological aspects.

31 Of course, for the metaphysical constructivist, there is no such thing as a 'flaw' in a strict sense. 'Flaw' could mean here, that an arbitrary observation became the foundation of a theory for contingent reasons, ignoring other equally credible possibilities. (Interestingly, it seems that one can hardly even formulate metaphysical constructivism with realistic notions like 'flaw' and 'credible'. But that is a whole different issue, which I want to ignore at this point.)

An underlying premise in Newton's approach was that it is an intrinsic, invariable characteristic of light to be perceived as having a certain color when it enters the eye. But it is easy to demonstrate that the same portion of light can be perceived differently in differing contexts and environments.[32] Phenomena like simultaneous contrasts, colored shadows or after-images cannot be explained from Newton's point of view.

Furthermore, without using realistic notions, a constructivist has to explain why the strong connection between optics and color theory has survived all those centuries and is still almost universally accepted by physicists. An obvious explanation could be Newton's importance for the development of modern physics. In the 18th century, Newton's theory gained hegemony and was defended in an increasingly dogmatic manner, as Sepper points out (1994:178).[33] Newton's optical theory was soon taken to conclusively explain how and why colors appear as they do. His theoretical framework of seeing light as consisting of different kinds of rays, which can be examined by means of instruments like prisms and lenses, became so dominant that alternative frameworks became unthinkable and conflicting evidence tended to be ignored.[34] The establishment of this dominance and how it survived up until today could be promising project for a constructivist. Maybe, one can make plausible how a different starting point could have made modern optics a whole different science with a whole different conceptual framework. Whether a more convincing constructivist analysis could actually be carried out or not, I leave open at this point.

32 According to the Norwegian physicist Holtsmark, Newton was confused in thinking that he explained the existence of the colored spectrum in terms of a physical model of light. In fact, he used experiments with the colored spectrum to explain one possible physical model of light (Holtsmark 1970:1235). If this is true, Newton's theory is just one possibility, and, thus, others may be thinkable and plausible. Certainly, one can question why a collection of highly artificial experiments in an artificial environment like a dark chamber should be able to demonstrate all the essential characteristics of color. And one could find it puzzling how these experiments continue to exert such a powerful influence on our thinking about light and color up until today.

33 One notable exception were painters. Their tradition as much as their practical experience inhibited them to believe that color was inherent to light alone (Gage 2008).

34 Goethe goes as far as equating Newton's followers in the 19th century with a closed circle of Catholic priests who control the interpretation of nature (Jackson 2008:387).

Appendix

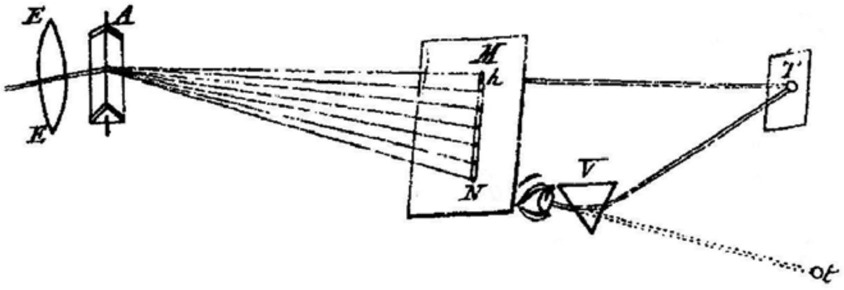

Fig. 4: Experiment 12 from Opticks, Book 1, Part 1, Proposition 5 (Newton 1704/1979:73). In Part 2, Proposition 2, Newton states that this experiment proves color immutability (1704/1979:122). The graph is taken from Shapiro 1996:116. In his trials in 1714, Desaguliers uses this experiment to show color immutability.

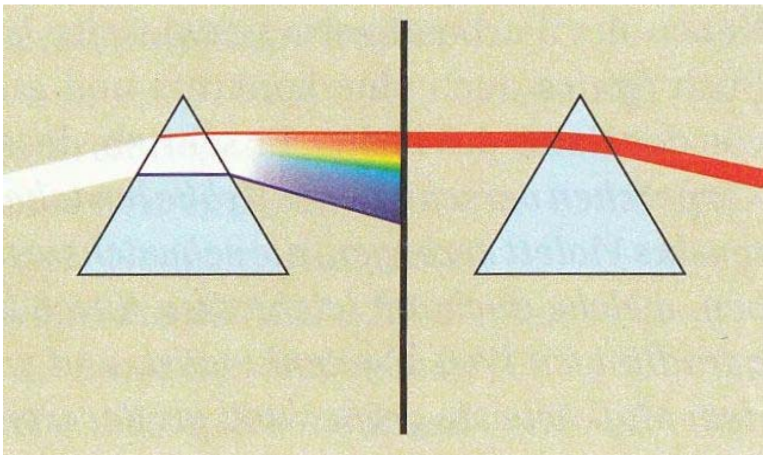

Fig. 5: Illustration in a contemporary German physics textbook for High School students. The image resembles the experimentum crucis and is supposed to illustrate that original colors cannot further be decomposed (Boysen et al 1999).

Year	Person	Place	Successful	Witnesses	Source
1666	Newton	Cambridge	Yes	Private	Schaffer 76
1670-71	Newton	Cambridge	No	Students	Schaffer 83
1672	Gregory	Edinburgh	Yes	Private	Shapiro 84
1672	Flamsteed	London	Yes	Private	Shapiro 84
1672	Hooke	London	Yes	Private	Schaffer 86
1674-76	Jesuits	Liège	No	Jesuits	Schaffer 88
1676	Royal Society	London	Yes	R.S. Members	Shapiro 77-78
1676	Lucas	Liège	No	Jesuits	Schaffer 89
1681	Mariotte	France	No	Private	Shapiro 97

Table 1: Replications of Newton's experimentum crucis before 1704. 'Success' is defined as being able to observe unequal refrangibility and color immutability. All

Year	Person	Place	Successful	Witnesses	Source
1707-14	Whiston	London	Yes	Lecture Course	Shapiro 93
1707	Poleni	Venice		Private	Shapiro 97
1707-08	Galiani	Rome		Private, Witnesses	Shapiro 96
1710	Bernoulli	Basel	Yes	Private	Shapiro 103
1714	Galiani	Rome	Yes	Public	Shapiro 96
1716	De Marian	Beziers	Yes	Private	Shapiro 101
1720's	Rizzetti	Venice	No	Private, Witnesses	Schaffer 97-98

Table 2: Replications of Newton's experimentum crucis after 1704."Success" is defined as being able to observe unequal refrangibility and color immutability. In case of Poleni, we only know that he replicated some experiments from the 'Opticks' and afterwards endorsed the Newtonian theory. Concerning Galiani, as he writes of observing color immutability in the experimentum crucis in 1715, he probably observed it in his first trial, too. All sources refer to pages in Shapiro 1996 or Schaffer 1989

Year	Person	Place	Comments	Witnesses	Source
1714	Desaguliers	London	Original	R.S. Members, foreign scientists	Shapiro 114
1719	Père Sébastien	Paris		Public	Shapiro 121
1720-21	's Gravesande	Netherlands	Published book	Private	Shapiro 123-24
1721	Gauger	Paris	No certainty about date	Public	Shapiro 121
1721	Algarotti / Zanetti	Bologna		Public	Shapiro 126-27
1728	Manfredi	Bologna		Public	Schaffer 98
1728	Desaguliers	London		Private, Italian Witnesses	Schaffer 98

Table 3: Replications of Desaguliers' experiments. One of the experiments is the experimentum crucis, but only with one boards as in Mariotte's trial. It is meant to prove unequal refrangibility. Desaguliers argues that, although the experimentum crucis appears to demonstrate color immutability, it is an imperfect method to create proper original colors. Thus, color immutability is proven by a different experiment in his trials. All replications appear to have been successful in those terms. De Marian is listed in figure 2, because he did not know of Desaguliers' trials. Rizzetti is listed in figure 2, because he still expected to observe color immutability in the experimentum crucis. All sources refer to pages in Shapiro 1996 or Schaffer 1989.

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