How many colours?[1]

Abstract

Isaac Newton's first optical paper (published in the *Philosophical Transactions* in February 1672) was controversial: Newton argued for a new theory of light and colour when no one else thought the old one was inadequate, and moreover he claimed certain truth for his new theory! A debate followed, in which Newton defended his claims against the objections of optical heavy weights such as Robert Hooke and Christiaan Huygens. One major sticking point between Newton and his critics concerned the number and division of colours. Newton argued that there is an indefinite number of 'primary' colours, but Hooke and Huygens objected to this inflated ontology. Each critic argued, for different reasons, that there were only two original colours. I examine Newton's responses to these objections. I argue that they are revelatory of Newton's unique methodology: a mathematico-experimental approach that eschewed 'hypotheses' in favour of 'theories'. I also show that we should read Newton's claim that there are an 'indefinite' number of colours in epistemic terms. Nowadays, Newton's first optical paper represents a landmark in the science of optics. Its exploitation of the correspondence between refraction and spectral colour, provided a new approach to the study of light. And its views on the properties and nature of light, set a new agenda for the field.

1 Introduction

In 1665, Cambridge University closed temporarily because of the plague and Isaac Newton went home to his family home of Woolsthorpe in Lincolnshire. He was there for almost two years. He was very active during this period: inventing calculus; conceiving the inverse-square law of universal gravitation; and discovering the chromatic composition of white light. These were Newton's *anni mirabiles* (years of miracles). One of Newton's legacies, which can be traced to this period, is the ROYGBIV colour spectrum—familiar from our

[1] [Acknowledgements]

schooldays. But this legacy conceals the controversial nature of Newton's theory of colour. One aspect of this controversy concerned the number and division of colours. Newton argued that there is an indefinite number of primary colours, but privileged seven of them. Optical heavyweights Robert Hooke and Christiaan Huygens objected to this inflated ontology, each arguing for different reasons that there were only two primary colours.[2]

In this paper, my aim is two-fold. Firstly, I aim to make sense of Newton's claims about the number of colours: in what sense are they indefinite, and in what sense is ROYGBIV privileged? I shall argue that Newton's claim that the number of colours is indefinite should be interpreted as an epistemological claim, rather than a metaphysical one. That is, Newton thought the number of colours was *unknown*, as opposed to literally indefinite. I shall then consider Newton's seven main colours. Newton started with five main colours—red, yellow, green, blue and violet—and then added orange and indigo later, in order to increase the analogy between colour and musical harmonics. I shall argue that, contrary to the Pythagorean interpretation of this work, Newton was making a point about perception, not about ontology. In other words, Newton's privileging of the seven main colours was a matter of aesthetics, not metaphysics. My second aim is to make sense of Hooke's and Huygens' criticisms of Newton's theory of colour and see what his responses tell us about his methodology. Their criticisms reveal them to be engaged in a different project to Newton's. Where Hooke presupposed a certain uniformity in light, and aimed to explain the *appearance* of different colours, Newton preferred to rely on his senses to tell him how many colours there are. Where Huygens appealed to explanatory virtues and saw a crucial role for speculative hypotheses, Newton strove to avoid speculation, focusing on what could be mathematically stated about the phenomena. In short, Newton had a unique methodology: a mathematico-experimental approach that prioritised observation and eschewed hypotheses.

I shall begin by outlining Newton's first optical paper, his 'New Theory', before moving onto the specifics of Newton's account of primary colours.

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[2] Hooke and Huygens were wave theorists, and each would write a book concerning optics: Hooke wrote *Micrographia* (1665) and Huygens wrote *Traité de la lumière* (1690).

2 Newton's 'New Theory'

Newton publicised his new theory of light and colour in a paper dated 6 February 1672.[3] It was read at a meeting of the Royal Society on 8 February 1672. Newton wasn't present, but news of its reception quickly reached him. The reception was positive: the Fellows were most impressed with his account of light and colours, and the experiments he described.[4] Notwithstanding these initial reports, the paper had caused some raised eyebrows. And not just because the main claim, that white light is heterogeneous, contradicted the established view of white light as 'pure' and homogeneous. Newton was arguing for a new theory when no one else thought the old one was inadequate. Moreover, he was claiming that his new theory was certainly true! As Zev Bechler put it:

> This was bad form. One doesn't just walk in, announce a fundamental inconsistency in accepted scientific beliefs, declare the need for a revolution, perform it, and walk out. Things are simply not done this way (Bechler, 1974: 117).

It's striking how much Newton does in such a short paper. He reveals a new phenomenon that, in turn, reveals a new property of light. He then uses this new insight to develop a new theory of colour—using it to explain the phenomena of coloured bodies. As we shall see, in revealing and explaining this new phenomenon, Newton addressed a range

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[3] Commentators have found the style of Newton's 'New Theory' enigmatic. Not only because it attempts to put forward some very sophisticated and novel scientific ideas in such a short paper (it's only about 5,000 words long!), but also because it combines an experimental focus with a quasi-geometrical approach to theorising. In fact, this paper is just the tip of the iceberg (Schaffer, 1986: 84). Newton had been developing the ideas since 1665, and had presented them his *Optical Lectures*, delivered between 1670 and 1672 (Newton, 1984).

[4] Henry Oldenburg, the founding Secretary of the Royal Society and the founding Editor of the *Philosophical Transactions*, wrote to Newton immediately to report on its reception:

> I can assure you, Sir, that it there mett both with a singular attention and an uncommon applause, insomuch that after they had order'd me to returne you very solemne and ample thankes in their name (which herewith I doe most cheerfully) they voted unanimously, that if you contradicted it not, this discourse should without delay be printed, there being cause to apprehend that the ingenuous & surprising notion therein contain'd (for such they were taken to be) may easily be snatched from you […] (Newton, 1959-1977: Vol. 1, 107)

of assumptions made by the received theory of light, eventually demonstrating that one of its central assumptions, that white light is homogeneous, is false.

2.1 A New Phenomenon

Newton described his discovery in an anecdotal style,[5] describing some experiments he performed in 1666, where he used glass prisms to examine "the celebrated *Phænomena* of *Colours*" (Newton, 1959-1977: Vol. 1, 92) (see figure 1 below for the initial experimental set-up). He wrote that what began as "a very pleasing divertisement, to view the vivid and intense colours produced thereby", soon yielded some unexpected results (Newton, 1959-1977: Vol. 1, 92). The coloured image produced by the passage of white light through the glass prism was oblong,[6] and yet, according to the received theory of light, the image should have appeared circular (Newton, 1959-1977: Vol. 1, 92) (see figure 2 below). So Newton set out to explain this discrepancy between the predicted result of this experiment and the actual result.

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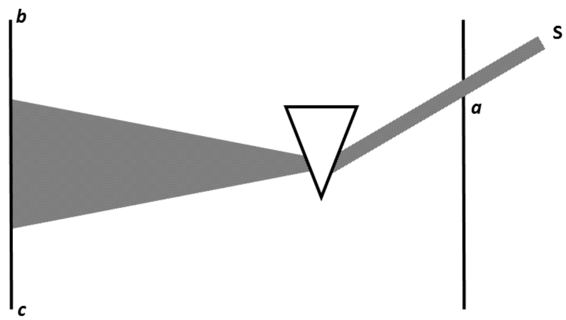
[5] In fact, this is almost certainly a 'rational reconstruction' of the events that took place during the plague years (1665–1666). As we shall see, the careful construction of the experimental set-up belies the feigned casualness with which Newton describes the experiment. For discussion on this point, see (e.g. Whiteside, 1966).

[6] More specifically, an elongated circle—curved at the ends and straight along the sides. In later work, Newton often depicted this shape in an idealised form, as a sequence of overlapping circles (e.g. Newton, 1952: 65, fig. 23). Newton reported that the length of the image was 5 times longer than its breadth (Newton, 1959-1977: Vol. 1, 92).



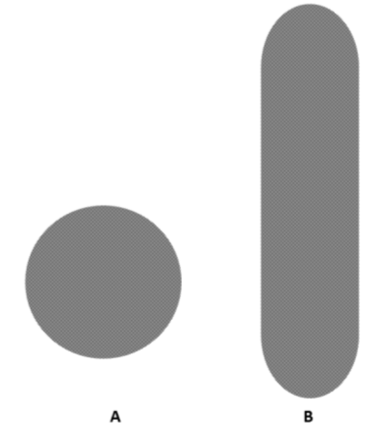


Figure 1 ***The set-up of Newton's first prism experiment***[7] **Figure 2** ***Comparison of results***[8]

It's worth pausing, for a moment, to understand why this result was unexpected. According to the received theory of light, white light is homogeneous, travels in straight lines and obeys the sine law.[9] From this theory, it followed that white light at equal angles of incidence should display equal angles of refraction when passing through the same medium. In other words, the white light from the sun should have retained its circular shape (i.e. the shape of the Sun's disc) when projected onto the screen. It might seem surprising that no one had noticed this discrepancy before. Indeed, what Newton was doing was by no means new: scientists had been studying light using prisms, lenses and globes for centuries.[10] How did Newton see something that no one else had seen? It seems that two features of Newton's experiment led him to his discovery. Firstly, in most prism experiments, some amount of elongation *was* expected. Indeed, as Sabra has pointed out:

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[7] The sunlight, S, enters through the aperture, *a*, passes through the prism and is projected onto the screen, *bc*.

[8] Where A is the expected result and B is the actual result.

[9] The sine law, also called 'Snell's Law' or the 'Snell-Descartes law', states that the ratio of the *sines* of the angles of incidence and refraction is a constant that depends on the medium through which the light passes.

[10] For an account of some of this history, see (Lindberg, 1981).

> […] except for one definite position of the prism, namely that of minimum deviation, a certain elongation of the image should have been expected. As we go on reading Newton's paper, however, we soon discover that the prism was fixed at precisely that position (Sabra, 1967: 235).[11]

And so, Newton's prism was in a very specific position—the *only position* at which no elongation was expected.

Secondly, most prism experiments had been carried out at short range, projecting images onto screens very close to the prism—at this distance, any elongation of the image would go unnoticed. In contrast, Newton was projecting the refracted image onto a screen at a distance of 22 feet. At this distance, the elongation effect would have been amplified. In other words, despite what he suggested, Newton, didn't begin by simply carrying out the standard optical experiments. He ran a novel and carefully constructed experiment to test a specific prediction, aiming to generate a maximally clear result.

Having observed the elongation of the image, Newton needed to explain it. He began with the assumption that the received theory of light was correct, and set about trying to identify the source of the discrepancy between prediction and observation. In doing so, he ensured the result truly clashed with the received theory, as opposed to an accidental false negative. He started with a series of experiments that established that the elongation resulted from neither variation in the thickness of the glass, an imperfection in the prism, nor the curving of rays[12] of light (Newton, 1959-1977: Vol. 1, 93-94). Then, maintaining his assumption of the sine law, he addressed the assumption that all the rays of light passing through the aperture have (roughly) the same angle of incidence—wondering if the amount of variation was significant after all. To test this suspicion, Newton calculated the maximum variation of incidence-angles that could be expected of light travelling from the sun at a given time, and computed the greatest possible elongation based on this variation. He

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[11] Moreover, Sabra notes, Newton's assertion (that the image should have appeared circular) is the only indication of the experimental set-up in this paper. This lack of clarity may well have been the source of the criticisms of Pardies (Newton, 1959-1977: Vol. 1, 131) and Linus (Newton, 1959-1977: Vol. 1, 317-319), both of whom objected that the elongated image could be explained by the received theory of light.

[12] In this context, a 'ray' is just some smallest part of light.

concluded that even the greatest possible variation would be too small to account for such a marked elongation. In other words, Newton identified a partial cause of the discrepancy, but not one which explained the full effect.[13] There remained a discrepancy to explain.

Having checked all his other assumptions, Newton then considered his assumption that all the rays of light travelling through the aperture were homogeneous with respect to their *refrangibility*[14]—that is, they were unified in terms of their disposition to refract. To test this assumption, Newton performed his '*experimentum crucis*'.

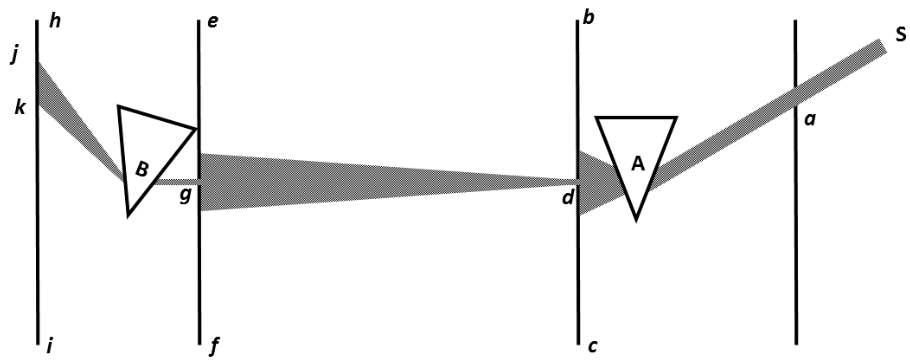

Figure 3 ***The experimentum crucis***[15]

The experimental set up is as follows (see figure 3 above). Firstly, a circular beam of light is projected through a prism and becomes elongated, just like in the first experiment. Then, instead of projecting the elongated image onto a screen, it is projected onto a series of boards with apertures in them, isolating a very narrow ray of light. Finally, this narrow ray of

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[13] Pardies would claim that this variation *was* enough to account for the effect (Newton, 1959-1977: Vol. 1, 131).

[14] *Refrangibility* is the degree to which light can refract when passing from one medium into another, or a "predisposition, which every particular Ray hath to suffer a particular degree of Refraction" (Newton, 1959-1977: Vol. 1, 96).

[15] In this experiment, light is projected from **S**, through aperture ***a***, where it is projected through prism **A** onto the board ***bc***, where most of the light is stopped. A small amount is allowed through the aperture ***d***, where it is stopped at the board ***ef***. A small amount of light is allowed through the aperture ***g***, where it is projected through prism **B**, and finally hits the screen ***hi***, forming the image, ***jk***.

light is projected through a second prism and onto a screen. The object of the experiment is to measure the angles of refraction by noting the placement of the projected image on the screen. By rotating the first prism, Newton was able to isolate different parts of the elongated image, and then note the placements of the light on the final screen. He noticed that the highest images on the screen (*hi*) were from the top part of the image (*bc*), and the lowest images on the screen (*hi*) were from the bottom part of the image (*bc*). Newton reported:

> And I saw by the variation of those places, that the light, tending to that end of the Image, towards which the refraction of the first Prisme was made, did in the second Prisme suffer a Refraction considerably greater then the light tending to the other end (Newton, 1959-1977: Vol. 1, 94-95).[16]

What Newton had noticed was that, for any given ray, refrangibility was a constant, but this disposition to refract varied between rays. That is, if a particular ray bent to an angle of x degrees after passing through the first prism, then it bent to an angle of x degrees after passing through the second prism as well. The outcome of this experiment led Newton to reject the assumption of homogeneity and conclude that *white light is a heterogeneous mixture of rays*:

> And so the true cause of the length of that image was detected to be no other, then that *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, 1959-1977: Vol. 1, 95).

In sum, in a few short pages, Newton had discovered a new phenomenon (the elongation of light), had revealed a new property of light (variation in refrangibility), and had thus refuted the received theory of light.

The implications of Newton's discovery were significant. For one thing, it had consequences for the development of telescopes, which he described in a fairly brief

[16] Commentators (e.g. Jalobeanu, 2014, Stein, 2004) have noted that Newton's description of this result is surprisingly awkward. This is probably due to the difficulty of describing the experiment without speaking about colours. We'll discuss the importance of this move below.

digression. Most of his contemporaries had attributed the imperfection of telescopic images to the imperfection of the lenses. However, Newton's discovery indicated a significant limitation that had nothing to do with glass-grinding techniques. That is, even if a lens could perfectly collect some homogeneous rays to a point, it could not do this for a heterogeneous mixture of rays.[17] This realisation led Newton to build a *reflecting* telescope. For, since "the Angle of Reflection of all sorts of Rays was equal to their Angle of Incidence" (Newton, 1959-1977: Vol. 1, 95),

> Optick instruments might be brought to any degree of perfection imaginable, provided a *Reflecting* substance could be found, which would polish as finely as Glass, and *reflect* as much light, as glass *transmits*, and the art of communicating to it a *Parabolick* figure be also attained (Newton, 1959-1977: Vol. 1, 95).

Newton's discovery also had implications for a new theory of colour. And it is to this colour theory that I now turn.

2.2 A New Colour Theory

In the final pages of his first paper, Newton announced a new theory of colour. Until this point, the received theory of colour was a *modificationist* view. By this view,[18] white light is pure and homogeneous, and colours are produced when white light is modified in some way—for instance, when it is mixed with shadow or manipulated through reflection and refraction. So far, Newton had demonstrated two things: firstly, that white light is not homogeneous, but rather is composed of rays of different refrangibilities; and secondly, that refrangibility is an *original* and *immutable* property of light. Newton now argued that colour is similarly original and immutable and that white light is composed of rays of every spectral

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[17] And indeed this was the case, until Chester Moore Hall succeeded in developing the achromatic lens, shortly after Newton's death.

[18] It is a little misleading to refer to *the* modificationist view, since many different ones were proposed by, e.g. Aristotle, Descartes and Hooke. However, these all had one main feature in common: colour is the result of the modification of white light. For a discussion of the various versions of this view, see (Zemplén, 2004).

colour.[19] And so, according to Newton, white light is a mixture of spectral colours, and the prism simply causes them to separate—grouping them according to their colours.

To understand Newton's inference, it is worth digressing for a moment to consider how Newton's *experimentum crucis* was received by his contemporaries.

To begin, what is an '*experimentum crucis*'? An *experimentum crucis* (lit. 'experiment at a crossroads') is an experiment designed to choose between two competing explanations. Newton's concept of an *experimentum crucis* is usually taken to be related to Bacon's *instantia crucis* (i.e. 'crucial instance').[20] For Bacon, crucial instances were a subset of 'instances with special powers' (ISPs). ISPs were experiments, procedures and instruments that were held to be particularly informative or illuminative of aspects of some inquiry into nature. These served a variety of purposes. Some functioned as 'core experiments', introduced at the very beginning of an investigation, and serving as the basis for further experiments. Others played a role later in the process. This included experiments that were supposed to be especially representative of a certain class of experiments, tools and experimental procedures that provided interesting investigative shortcuts, and model examples that came close to providing theoretical generalisations.

Crucial instances were part of a subset of ISPs that were supposed to aid the intellect by "warning against false forms or causes" (Bacon, 2004: 445). When two possible explanations seemed equally good, then the crucial instance was employed to decide between them. To this end, it performed two functions: the negative function was to eliminate all possible explanations except the correct one; the positive function was to affirm the correct

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[19] Here's a fun fact: Newton was the first to use the term 'spectrum' to describe the coloured band into which a beam of light is decomposed by means of a prism (OED, December 2015).

[20] Bacon used the term '*instantia crucis*' (i.e. a 'crucial instance') in the *Novum Organum*, but there is some confusion in the literature as to who first introduced the related term '*experimentum crucis*'. Peter Anstey and Michael Hunter have argued that, while the notion is often attributed to Hooke, it in fact should be attributed to Boyle, who introduced the notion in his *Defence against Linus* (1662) (Anstey & Hunter, 2008: 112).

explanation.[21] Newton's *experimentum crucis* performed a similar role,[22] and in doing so, revealed a new property of white light.

In his first paper, Newton made two claims in relation to the *experimentum crucis*:

1) White light is composed of rays of many refrangibilities; and
2) White light is composed of rays of many spectral colours.

There is a standard account of this experiment, according to which the result was (2). On this account, the *experimentum crucis* was designed to decide between two views on colour: the modificationist view and Newton's view, that spectral colours are not generated by modification when the white light passes through the prism, but are *already present* in the light. This was how Hooke interpreted the experiment, and he thought it failed to decide conclusively in favour of Newton's view. In other words, Hooke denied that the experiment was a crucial experiment.[23] He wrote:

> But how certaine soever I think myself of my hypothesis, wch I did not take up without first trying some hundreds of expts; yet I should be very glad to meet wth one Experimentum crucis from Mr Newton, that should divorce me from it. But it is not that, which he soe calls, will doe the turne; for the same phænomenon will be salved by my hypothesis as well as by his without any manner of difficulty or straining […] (Newton, 1959-1977: Vol. 1, 110-111)

Let's try to see the experiment as Hooke saw it. Hooke saw white light enter the first prism and a spectrum of colours come out the other side. Then, after isolating a single colour, he saw, say, red light enter the second prism and red light come out (see figure 4 below for a simplified analysis). While he agreed that (2) was a *possible* explanation of the

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[21] For a discussion of the role of the *instantia crucis* in Bacon, Boyle and Hooke, see (Dumitru, 2013). For a discussion of the role of the *experimentum crucis* in Newton's *Principia*, see (Walsh, 2015).

[22] It is worth noting, however, that Bacon's notion of *instantia crucis* appears to be broader than Newton's notion of *experimentum crucis*: where the former refers to observations and experiments, the latter refers almost exclusively to experiments. In this sense, Newton's *experimentum crucis* is similar to Boyle's (Anstey & Hunter, 2008: 112). For a discussion of the relationship between Newton's *experimentum crucis* and Bacon's *instantia crucis*, see (Hamou, Forthcoming).

[23] In fact, Hooke was one of the few scientists who was able to replicate Newton's experiment.

phenomenon, he didn't think it was the *only* explanation. As far as Hooke was concerned, the experiment showed that, once the light becomes red, it doesn't change through refraction. He saw no reason to conclude that the red *must* have already been in the white. An alternative explanation—one that, to his mind, Newton's experiment hadn't ruled out—was that the prism irrevocably modified the light.

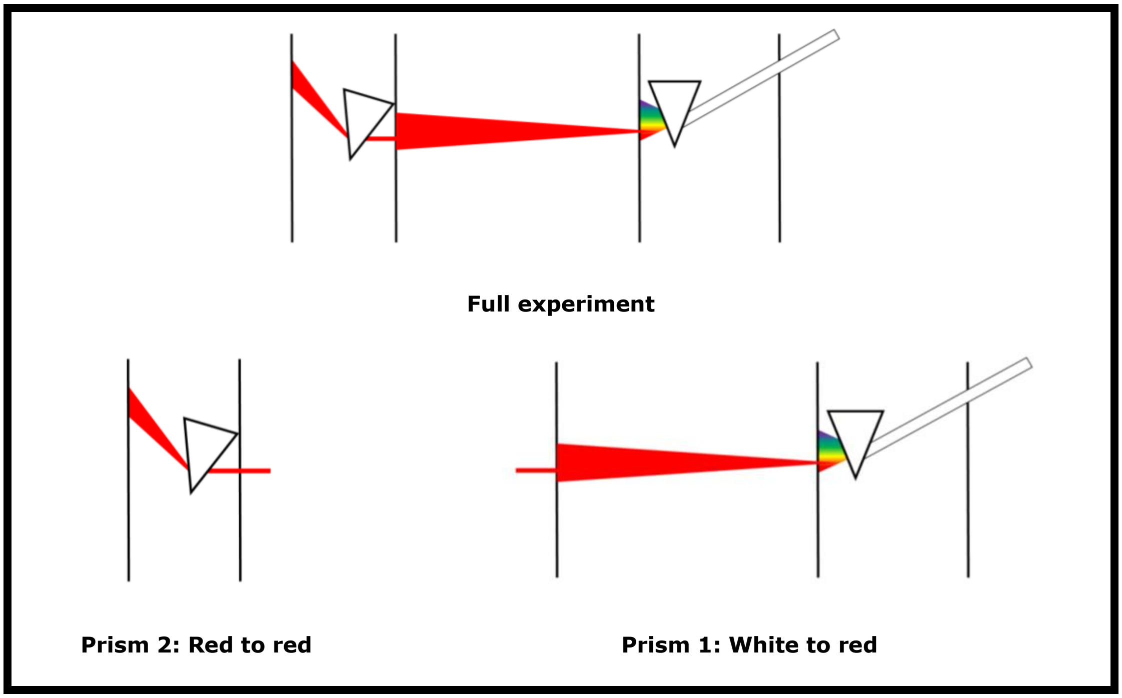

Figure 4 ***Analysis of the experimentum crucis in colour***

As we saw in the previous section, however, Newton did not present the *experimentum crucis* in this way. For one thing, as Phillipe Hamou has recently pointed out, Newton didn't mention the rival, modificationist, view at all in his first paper (Hamou, Forthcoming). In fact, the experiment was demonstrating a new effect—one for which there was no received explanation. And for another thing, Newton took the result to be (1), above; this was an experiment on white light and its refrangibility; not colour. This is crucial: Newton was concerned with geometrical factors such as the length of the image, the position of the image on the wall, the distance from the aperture to the prism and the prism to the wall, and the angles of incidence and refraction. Newton's initial surprise was the *elongation* of the image. *This* was what he set out to explain. Recall also that the other experiments he conducted in order to test various 'suspicions' also focused on geometrical factors, as opposed to the colour of the light. In fact, as Hamou and Jalobeanu have noted, the *experimentum crucis* merely makes explicit what was revealed by the preceding experiments (Hamou, Forthcoming, Jalobeanu, 2014). Namely, that the elongation effect is not an artefact of the experimental set-up, but due to a property of light.

Let's consider the experiment as Newton saw it. He conceived of the experiment as a series of lines and angles. The light ray entered the prism at a certain angle and exited the prism at another angle: if light bent *x* degrees at the first prism, it also bent *x* degrees at the second prism (see figure 5 below for a simplified analysis). That is, each time a particular ray passed through a prism it refracted to precisely the same degree. For Newton, this demonstrated that refrangibility is an original and unchangeable property of light, not an effect of the prism. And so, in reply to Hooke, Newton explained that the *experimentum crucis* demonstrated that rays of different colours are differently refrangible, and that this is not something that is caused by the prism (i.e. by "rarefying & splitting of rays" (Newton, 1959-1977: Vol. 1, 187)). Rather, this is a disposition that every ray already has—originally and immutably. The prism had merely separated what was already distinct. Having established (1) by experiment, Newton then inferred (2). And so, Newton's inference can be summarised as follows:

P1. White light is composed of rays of many refrangibilities (1).

P2. There is a one-to-one correspondence between refrangibility and original colour.[24]

C. White light is composed of rays of many spectral colours (2).

[24] In his *Opticks*, published in 1704, Newton offers experimental support for this proposition.

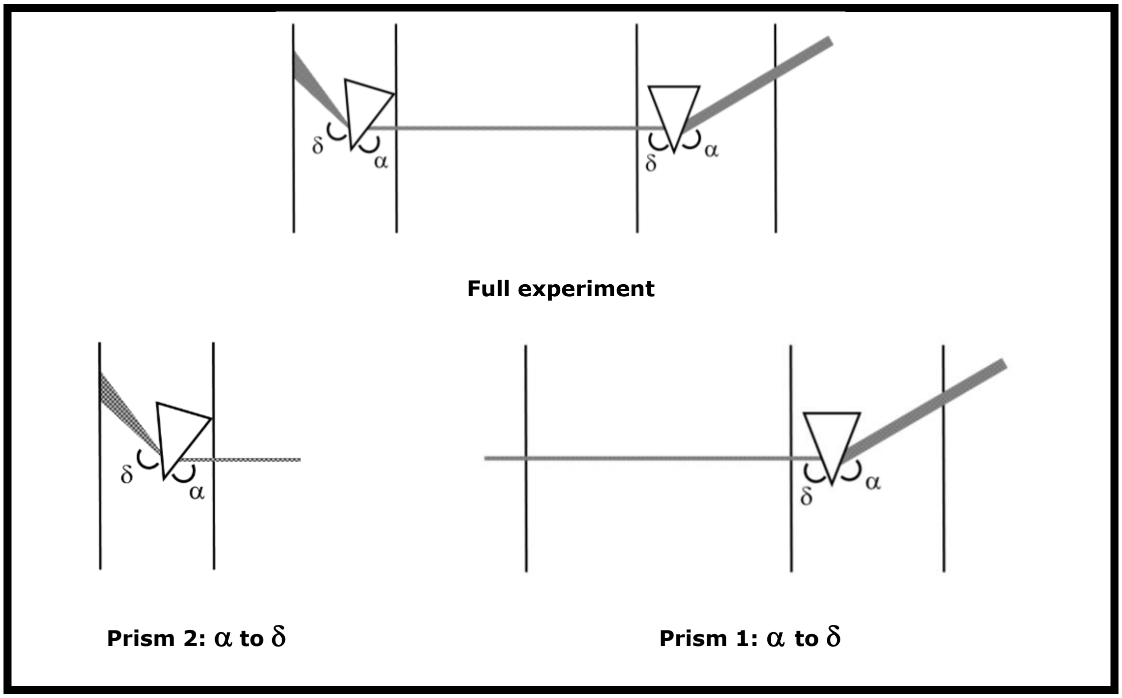

Figure 5 ***Analysis of the experimentum crucis in black and white***

Newton's interpretation of the *experimentum crucis* illuminates two features of his methodology. Firstly, it emphasises the importance of precise measurement in his quest for certainty. It would have been difficult to measure precisely changes in colour, but Newton was able to measure the degrees of refraction by measuring the positions of the images on the wall. He recorded observations that are measurable, quantitative and precise, since *this* data could be employed to reason mathematically to certain conclusions. Newton wanted to establish physical properties with certainty, so it is no surprise that he eschewed talk of colour to focus on geometric properties. Secondly, it demonstrates the deductive step in the argument. Newton's claim that white light is composed of rays of all the spectral colours, and his further claims about the properties of light, are inferred from his first claim. Hooke saw the inference from observation to (2) as a single, experimental step. Newton saw the inference from observation to (2) as two steps, one experimental (i.e. from the *experimentum crucis* to P1), one deductive (i.e. P1 and P2 together entailed C). Newton had managed to integrate the study of colour with geometrical optics—an impressive achievement!

Now let's return to Newton's new colour theory.

After his initial insight on the relationship between refrangibility and colour, Newton developed a theory of colours, which he outlined in thirteen propositions (summarised in table 1 below). It's worth noting a few key features of this theory. Firstly, Newton distinguished between original colour, namely, colour as an inherent and immutable property of light, and compound colour, colour that is produced by combining light of different colours. Newton argued that each ray has an original colour, and this is an unchangeable property of the ray.[25] However, when combined with light of a different colour, it could *appear* to change colour. Importantly, when mixed, each ray would retain its original properties.

Newton thought that all the original colours could be replicated by combining colours—their differences would only become apparent when they were separated again. And so, you could have two samples of, say, yellow light that *look* the same but, when refracted, reveal different properties: homogeneous yellow light remains yellow-coloured even when refracted; whereas compound yellow light breaks into its component colours, say, red and green.

The ability to separate light into its component colours highlights another feature of Newton's theory: there is a one-to-one correspondence between spectral colour and refrangibility. And so, light of the same colour has the same disposition to refract. This is why, when white light passes through a prism, a spectrum is produced: the rays gather together into their homogeneous groups. The causal relationship between refraction and colour was frequently misunderstood by Newton's critics. They often took Newton to be claiming that refrangibility somehow *caused* the production of colour.[26] In fact, Newton

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[25] It is worth noting that, strictly speaking, Newton does not consider rays of light to be coloured. In the *Opticks*, he included a definition:

> The homogeneal Light and Rays which appear red, or rather make Objects appear so, I call Rubrific or Red- making; those which make Objects appear yellow, green, blue and violet, I call Yellow-making, Green-making, Blue-making, Violet-making, and so of the rest. And if at any time I speak of Light and Rays as coloured or endued with Colours, I would be understood to speak not philosophically and properly, but grossly, and accordingly to such Conceptions as vulgar People in seeing all these Experiments would be apt to frame. For the Rays to speak properly are not coloured. In them there is nothing else than a certain power and disposition to stir up a Sensation of this or that Colour. For as Sound in a Bell or musical String or other sounding Body, is nothing but a trembling Motion, and in the Air nothing but that Motion propagated from the Object, and in the Sensorium 'tis a Sense of that Motion under the form of Sound; so Colours in the Object are nothing but a Disposition to reflect this or that sort of Rays more copiously than the rest; in the Rays they are nothing but their Dispositions to propagate this or that Motion into the Sensorium, and in the Sensorium they are Sensations of those Motions under the forms of Colours (Newton, 1952: 124-125).

[26] This shows how deeply entrenched modificationist intuitions were!

thought that refrangibility causes the production of colour only insofar as it causes rays to separate into their different colours, thus, making the original colours visible. Newton did not know *why* this one-to-one correspondence occurs, only that it *does* (Newton, 1959-1977: Vol. 1, 265). As far as Newton was concerned, the only difference between white light and any other compound colour was that there was no original white: white could only be produced by combination. This contradicted the received view that white light was homogeneous and that colours were created by *modification* of white light.

Prop 1	Colours are not caused by refraction or reflection but are *original properties* of rays of light.
Prop 2	There is a *one-to-one correspondence* between colour and refrangibility.
Prop 3	The colour and refrangibility of any given ray are *constant and unchangeable*.
Prop 4	The colour of light can be changed by *composition and decomposition*. But such changes are not real, only apparent – each individual ray always retains its original colour.
Prop 5	There are two kinds of colours: *original* and *compound*.
Prop 6	New (*compound*) colours, which look the same as original colours, are created by combining original colours.
Prop 7	Whiteness is not an original colour, but a *compound of all the original colours*.
Prop 8	White light is a mixture of all original colours *in equal amounts*. If there is more or less of some particular colour, then the light will not be white.
Prop 9	A prism produces coloured light by *separating white light* into its constituent rays by refraction.
Prop 10	Rainbows appear because *water droplets refract sunlight*.
Prop 11	Some bodies appear one colour in one position and another colour in another position because they are *illuminated by*, and so *transmit*, different coloured light.
Prop 12	If two glass vessels are filled one with red liquid and the other with blue liquid, separately they are transparent, but together they become opaque. This is because one only transmits red rays and the other only blue rays, so *together they do not transmit any rays.*
Prop 13	*All coloured bodies* obtain their colour via refraction, reflection and transmission of the rays of light that illuminate them.

Table 1 Summary of Newton's new theory of light (as presented in February 1672)

Now that we have the general shape of Newton's theory of colour, let's look more closely at his claims about original or primary colours.

3 On the number and division of colours

In this section, I explain Newton's position on the number and division of colours. I argue that, for Newton, (1) there are many colours (not simply the seven of ROYGBIV) and (2) they are 'indefinite' in an epistemic sense—that is, there are many of them (in fact, one for each angle of refraction!), and we don't currently know how many.

Newton stated his position in his expansion of proposition 5 (paraphrased in table 1 above):

> 5. There are therefore two sorts of colours. The one original and simple, the other compounded of these. The original or primary colours are, *Red, Yellow, Green, Blew,* and a *Violet-purple*, together with Orange, Indico, and an indefinite variety of Intermediate gradations (Newton, 1959-1977: Vol. 1, 98).

As we've already noted, proposition 5 draws a distinction between *original* and *compound* colours. Original colours are the inherent, immutable properties of individual rays of light. When lights of two different colours are combined, they will produce some other colour—a compound. But each ray retains its original colour, which can be seen when the compound is separated (say, using a prism) into its component colours.

So, according to Newton, there are two kinds of colours: original (or primary) and compound. But how many original colours are there? The above passage might seem confusing. Newton first names the five colours of the rainbow, then he adds two more colours, giving us seven main colours (which eventually became known as ROYGBIV).[27] But then he adds that there are "an indefinite variety of Intermediate gradations". So, according to Newton, there are seven main colours and also a number of intermediate colours. This passage raises two questions. (1) what does Newton mean by 'indefinite'?

[27] It is not clear in what sense Newton's seven-colour spectrum was new, since the notion of a seven-colour spectrum dates back at least to Aristotle. Establishing the originality of Newton's spectrum is beyond the scope of this paper.

And (2) is there anything special about the seven main colours? I'll address each of these questions in turn.

3.1 What does Newton mean by 'indefinite'?

We should interpret 'indefinite' *epistemically*, not metaphysically. That is, Newton was saying that the number of original colours is *uncounted* and therefore unknown, as opposed to *uncountable*. Here's why.

Firstly, to anyone who read his 'New Theory', it was clear that Newton thought that light was corpuscular. That is, light is composed of miniscule bodies or atoms. He wrote:

> For, since Colours are the *qualities* of Light, having its Rays for their intire and immediate subject, how can we think those Rays *qualities* also, unless one quality may be the subject of and sustain another; which in effect is to call it *substance*. We should not know Bodies for substances, were it not for their sensible qualities, and the Principal of those being now found due to something else, we have as good reason to believe that to be a Substance also (Newton, 1959-1977: Vol. 1, 100).

Here, Newton was arguing that, since colour is a sensible quality of light, light must be a substance. That is, colour must be a property of particles, or corpuscles, of light.[28] While he tried to keep them separate,[29] Newton's corpuscularian suppositions seem to have influenced his theoretical claims. For example, he argued that original colours remain distinct and unaltered when they are mixed to form white light.[30] He was thinking of rays as analogous

[28] But Newton was cautious. He said that although he had established that light is heterogeneous, "to determine more absolutely, what Light is, after what manner refracted, and by what modes or actions it produceth in our minds the Phantasms of Colours, is not so easie" (Newton, 1959-1977: Vol. 1, 100). He said that he was not willing to speculate any further on these matters.

[29] I discuss Newton's separation of hypotheses and theories below.

[30] Sabra has pointed out that this was barely intelligible to wave theorists (Sabra, 1967: 280-282).

to, say, grains of sand or powder: the particles mix together, but each retains its separate identity.[31] In short, Newton conceived of light as composed of discrete particles.

Secondly, as we've seen, Newton, indexed original colour to refrangibility: that is, there is an original colour for each degree of refraction. This is indicated in proposition 2 in Newton's 'New Theory' paper (see table 1 above), but stated explicitly in a letter to Huygens in 1673:

> 3. There are as many simple or homogeneal colours as degrees of refrangibility. For to every degree of refrangibility belongs a different colour by Prop: 2. And that colour is simple by Def: 1. & 3. (Newton, 1959-1977: Vol. 1, 293).[32]

Thirdly, Newton thought that refrangibility is an original and immutable property of light. Since light is corpuscular, refrangibility is a property of each discrete particle of light. And so the number of degrees of refrangibility must be countable in principle—and by extension, the number of colours must be in principle definable.

And so, by 'indefinite' Newton must have meant 'uncounted' rather than 'uncountable'. The notion of colour as metaphysically indefinite is incompatible with Newton's thinking of light in corpuscularian—and therefore discrete (and countable)—terms. For colour to be metaphysically indefinite, Newton needed to argue that refrangibility is indeterminate and uncountable—but then he could not have held refrangibility to be an original property of light (and therefore indexed to colour).

3.2 Is there anything special about the seven main colours?

As I've mentioned, Newton is credited with the 'discovery' of ROYGBIV, which involved adding two extra colours to the spectrum, bringing the total to seven. This might seem strange, given that Newton argued that there were an indefinite number of original colours.

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[31] Newton recognised this metaphysical commitment when he said: "Besides, who ever thought any quality to be a heterogeneous aggregate, such as Light is discovered to be" (Newton, 1959-1977: Vol. 1, 100). In other words, substances can be combined in this way, but qualities cannot.

[32] In this letter to Huygens, Newton presented a new version of his theory of colours in a series of definitions and propositions.

It wasn't until 1675, when Newton published a follow-up paper, his 'Hypothesis concerning light and colours' (hereafter, 'Hypothesis'), that the reason became clear:[33] Newton wanted to improve the analogy between spectral colour and harmonics. This has often been interpreted as Pythagorean—the thought being that there is something mystical or metaphysically special about the mathematical relationships which manifest in shapes, sounds, numbers and visual angles. And so Newton has often been interpreted as arguing that the seven main colours are ontologically privileged. In this section, however, I argue that Newton doesn't think there is anything metaphysically special about the seven main colours.

Let's start by examining the context in which Newton introduced his analogy between spectral colour and harmonics: his 'Hypothesis'. The account Newton laid down in this paper is composed of the following six hypotheses:

1. There is an 'æthereal medium', which is similar to air, but rarer, more penetrating and more strongly elastic (Newton, 1959-1977: Vol. 1, 364).
2. Æther vibrates, carrying sounds, smells and light. While the vibrations differ in size, they are on the whole (much) smaller and swifter than the vibrations of air (Newton, 1959-1977: Vol. 1, 366).
3. Æther penetrates and passes through the pores of solid substances such as crystal, glass and water. But æther is less dense within those pores than without (Newton, 1959-1977: Vol. 1, 366-367).
4. Light is neither the æther itself, nor the vibrations, but a substance that is propagated from 'lucid' bodies and travels through the æther (Newton, 1959-1977: Vol. 1, 370).
5. Light warms the æther and the æther presses on the light. Thus, the mutual action of light on æther, and æther on light, explains how light is reflected and refracted (Newton, 1959-1977: Vol. 1, 371).
6. The rays (or bodies) of which light consists differ from one another physically. These physical differences are unchangeable and cause the rays to be different colours. This

[33] Newton sent his 'Hypothesis' to the Royal Society in December 1675, but manuscript evidence shows that the bulk of this paper was completed in 1672.

> explains how it happens that colour and refrangibility are unchangeable properties of light (Newton, 1959-1977: Vol. 1, 376).

Newton's aim in this paper was of an entirely different kind to that of his 'New Theory'. There, Newton was describing observed phenomena of light and inferring its properties. He 'proved' these propositions about light by experiment—the *experimentum crucis*. Here Newton was in the business of hypothesising about the nature of light: the unobserved mechanism which caused the observed phenomena. He didn't attempt to 'prove' these theories, but just to make them plausible. He emphasised that he only intended his account to be a *possible* explanation. And so, the kind of support Newton offered for these hypotheses was also different to that from his 'New Theory'. Here, he drew on various experiments and observations, which he took to underwrite the plausibility of hypotheses 1-6, either by analogy, direct empirical support, or by demonstrating explanatory power. This is a stark contrast to the certainty he claimed from the *experimentum crucis*.

In his discussion of hypothesis 6, Newton introduced his analogy between spectral colour and harmonics. He argued that the "principall Degrees" of colour—red, orange, yellow, green, blue, indigo and violet—may be proportional just as musical tones are (Newton, 1959-1977: Vol. 1, 376). This wasn't pure speculation. To establish the intervals between the seven 'principall' colours on the spectrum, he projected a spectrum onto a piece of white paper using a prism. He held the paper while an assistant marked the parts of the image where each colour was "most full & brisk, & also where he judged the truest confines of them to be" (Newton, 1959-1977: Vol. 1, 376).[34] He then superimposed a monochord[35]

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[34] Newton explained that he employed an assistant to make the judgements "partly because my owne eyes are not very criticall in distinguishing colours, partly because another, to whome I had not communicated my thoughts about this matter, could have nothing by his eyes to determin his fancy in makeing those marks" (Newton, 1959-1977: Vol. 1, 376).

[35] A monochord is a musical stringed instrument wherein a single string is stretched over a sound box. The string is fixed at both ends, and one or more movable bridges are manipulated to demonstrate mathematical relationships between sounds. It was used as a scientific instrument to illustrate the mathematical properties of musical pitch.

on the spectrum and claimed that the seven colours correspond to the division of the monochord into seven notes (see figure 6 below). Newton wrote:

> And possibly colour may be distinguisht into its principall Degrees, Red, Orange, Yellow, Green, Blew, Indigo, and deep Violett, on the same ground, that sound with an eighth is graduated into tones (Newton, 1959-1977: Vol. 1, 376).

Newton made a similar argument in his *Opticks* (1704), describing the seven principal colours as "divided after the manner of a Musical Chord" (Newton, 1952: 126), and as "proportional to the seven Musical Tones or Intervals of the eight Sounds, *Sol*, *la*, *fa*, *sol*, *la*, *mi*, *fa*, *sol*" (Newton, 1952: 154).[36]

This work has often been viewed as Pythagorean, in that Newton was apparently trying to explain other natural phenomena in terms of musical harmonies (e.g. Gouk, 1988, Pesic, 2006). If this were the case, then Newton should be interpreted as assigning some sort of ontological or metaphysical priority to the seven main colours. Niccolò Guicciardini, however, has recently offered an alternative interpretation of this work (Guicciardini, 2013). Guicciardini argues that, if we consider the context in which this analogy is introduced, we should see that Newton isn't being Pythagorean at all. He doesn't think there is anything mystical or metaphysically special about the relationship between colour and sound. Rather, as we shall see, he is making an aesthetic point—and uses the analogy between optics and harmonics to develop a theory of perception.

[36] He continued to hold, however, that there were many degrees of colour: "the Spectrum *pt* formed by the separated Rays [...] appear tinged with this Series of Colours, violet, indigo, blue, green, yellow, orange, red, together with all their intermediate Degrees in a continual Succession perpetually varying. So that there appeared as many Degrees of Colours, as there were sorts of Rays differing in Refrangibility" (Newton, 1952: 122).

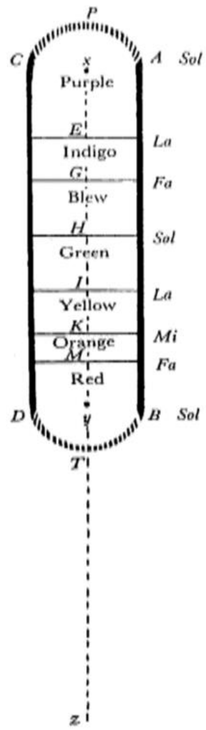

Figure 6 ***Newton's demonstration of the analogy between harmonics of colour and sound*** [37]

Newton introduced hypothesis 6 to explain colour vision. On his account, corpuscles of light travel through the æther, causing the æther to vibrate—different colours produce vibrations of different sizes. These æthereal vibrations travel along the 'optick nerves', causing us to perceive colour.[38] The analogy between harmonics and colour is supposed to contribute to this account by unifying sound and vision into a theory of perception. In his discussion of hypothesis 2, Newton drew a similar analogy between light and sound. He argued that, just as "in a ring of Bells the sound of every tone is heard at two or three miles distance, in the Same Order that the bells are Stroke", it is possible for æthereal vibrations to vary in size but not speed (Newton, 1959-1977: Vol. 1, 366). This suggests that Newton was interested in explaining colour vision in terms of æthereal vibrations and developing a

[37] Analogy between the prismatic spectrum and the musical scale (a Dorian mode equivalent to playing the white notes on a piano keyboard from D to d) (Newton, 1959-1977: Vol 1, 376).

[38] For a discussion of Newton's theory of vision, see (Hamou, 2014).

unified account of perception—he doesn't seem to think there is any mystical correspondence between colour and harmonics.

For Guicciardini, then, Newton's analogy between harmonics and colour is motivated by his interest in the physiology of perception. I now want to build on this account, and argue that for Newton, the seven-colour spectrum is merely an *aesthetic*, or *perceptual* phenomenon. That is, there is nothing metaphysically special or privileged about ROYGBIV but, as a matter of contingent fact about our visual apparatus, we tend to emphasise those aspects of the spectrum. Such a suggestion nicely explains how Newton could, on the one hand, claim that there are many original colours, and on the other hand, emphasise these seven colours for apparently non-arbitrary reasons. This is a bit of speculation on my part, but it is not wholly unfounded. Firstly, the consistency of the reading lends it some plausibility. Secondly, it is not entirely without textural support. Consider the following passage from Newton's manuscript 'Of Musick':[39]

> 5. An 8^{th} is next divided into a third major & 6^{th} minor, & lastly into a 3^{rd} minor & 6^{th} major these are all the concords contained in an Eighth. Hereto annex a discourse of the 3^{rd}s & 6^{th}s.
>
> The notes in order of concordance
>
> eighth. 5^{th}. 3^{rd} maj. 4^{th}. 6^{th} maj. 3^{rd} min. 6^{th} min. 2^{nd} maj. 7^{th} maj. 7^{th} min. 2^{nd} min. 5^{th} min.
>
> But as too sudden a change from less to greater light offends the eye by reason of that, the spirits rarefied by the augmented motion of the light too violently stretch the optic nerve: so the sudden passing from grave to acute sounds is not so pleasant as if it were done by degrees, because of too great a change of motion made thereby in the auditory spirits. And as a man suddenly coming from greater to less light, cannot discern objects thereby so well, as if he came to it by degrees or as when he hath stayed some while in the lesser light (by reason that the motion of the spirits in the optic nerve caused by the greater light, doth, until it be allayed; disturb so as it were drown the motion of the weaker light) so if the slower motion of the lower sound immediately succeed the much more small motion of the higher its impression on the auditory spirits—being then less perceptible, the lower sound must be less pleasant than if the step had been graduated. Thus a little heat is least perceptible to one newly come from a greater. Corollary: 1. The distance of sounds adds to the imperfection of their concordance.

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[39] This manuscript is found in a notebook kept by Newton during 1664-1666 (Cambridge University Library Add. Ms. 4000, ff. 137–143). I quote this passage from (Pesic, 2006: 299-300). In an attempt at clarity, I have flouted convention by regularising Newton's spelling and omitting his editing marks.

> Corollary. 2: Tis better to descend than ascend by leaps the first making the highest sound harsher; the second making the lower only less perceptible […]

Here, Newton is not concerned with colour but brightness of light, however notice three things about this passage. Firstly, Newton relies on experiential judgements, such as 'pleasantness' and 'harshness', to develop his analogy between sound and light. This supports my suggestion that Newton's focus is aesthetic, rather than metaphysical. Secondly, he offers physiological explanations for the analogy. And thirdly, he begins by drawing an analogy between sound and light, but then extends the analogy to heat. The latter two points support the above suggestion that Newton is interested less in the metaphysical significance of mathematical proportions, and more interested in the physiology of perception.[40]

Having established that Newton indeed thought there were many colours, let's now consider how his critics took the news.

4 The debate

As we've seen, Newton's 'New Theory' sparked some lively debate. This was no doubt due, in large part, to the brevity of the paper—and the fact that Newton's claims to certainty seemed epistemically reckless. However, several of Newton's critics also perceived serious conceptual difficulties with his new theory of light and colours. One issue, raised by both Huygens and Hooke, concerned the number and division of primary colours. Newton argued that there is an indefinite number of 'primary' colours, but Hooke and Huygens objected to this inflated ontology. Each critic argued, for different reasons, that there were only two primary colours. In this section, I'll examine Huygens' and Hooke's criticisms. I'll argue that these criticisms stemmed, not simply from a misunderstanding of Newton's (admittedly brief) characterisation of his view, but also from the fact that they and Newton had very different research programmes.

[40] Moreover, my speculation has other potential routes to testing (which I won't explore here). For instance, if Newton thinks that ROYGBIV is a set of aesthetic categories, he will likely think the same of musical scales—and potentially take a similar angle on other distinctions of this kind. If more of Newton's manuscripts are examined in this light, and a pattern emerges, this would lend further support.

4.1 Newton versus Hooke

As we've seen, Newton argued that the number of different original colours was indefinite. However, Hooke did not think it necessary to postulate more than two colours. He wrote:

> But as to the fifth [proposition], yt there are an indefinite variety of primary or originall colours, amongst which are yellow, green, violet, purple, orange &c and an indefinite number of intermediat gradations; I cannot assent thereunto, as supposing it wholy useless to multiply entites wthout necessity: since I have elswhere shewn, that all the varietys of colours in the world may be made by the help of two (Newton, 1959-1977: Vol. 1, 113).

According to Hooke, many apparent differences in the *colour* of light were really differences in the *amount* of light. And so, to claim that there are more than two primary colours is to multiply entities beyond necessity. In response, Newton argued that Hooke was begging the question—instead of presupposing uniformity, we should take the appearances of things as phenomena to be explained.

Newton considered Hooke's experiment involving two vessels filled with coloured liquid.[41] In one, the liquid was coloured by 'tincture of *Aloes*'. The liquid was mostly red, but around the edges it was yellow. In the other vessel, the liquid was coloured with a copper solution. The liquid was mostly blue, but around the edges it was indigo. Newton argued:

> Now if Mr Hook contend that all the *Reds* & *Yellows* of the one liquor, or *Blews* & *Indicos* of the other, are onely various degrees & dilutings of the same colour, & not divers colours, that is a begging of ye Question […] Certainly it is much better to believe our senses informing us that Red & Yellow are divers colours, & to make it a Philosophicall Query, why the same Liquor doth according to its various thicknesse appear of those divers colours, then to suppose them to be the same colour because exhibited by the same liquor (Newton, 1959-1977: Vol. 1, 179).

In contrast with his own approach, Newton noted that Hooke appeared to be concerned with theoretical virtues such as subtlety and intelligibility, rather than epistemic virtues (i.e. those that are directly related to empirical support and truth). He thought that Hooke was "valuing uncertain speculations for their subtleties, or despising certainties for

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[41] Here, Newton was referring to experiments described in Hooke's *Micrographia* (Hooke, 1966/1665: 48), which Hooke mentioned in his response to Newton's paper.

their plainesse", when he ought to have been making "a sincere endeavour after knowledge" (Newton, 1959-1977: Vol. 1, 171). Newton thought that Hooke should be concerned with whether or not *the evidence supports the new theory*; not whether or not his *hypothesis fits the theory*.[42]

4.2 Newton versus Huygens

Huygens did not dispute Newton's experimental results. Furthermore, he allowed that Newton was probably correct about some of the properties of light and colours he described.[43] However, he raised two main objections to Newton's paper.

Huygens' first objection concerned Newton's proposition that white light is composed of an indefinite number of colours. Huygens argued that two primary colours, yellow and blue, are sufficient to produce all the other colours (including white). He gave two reasons for limiting the number of primary colours to two. (1) A methodological reason: it is easier to give a mechanical explanation when there are fewer colours to explain. Such an explanation is simpler, and therefore better. (2) An empirical reason: it is possible to produce white light (and all the other colours) by mixing just two primary colours, blue and yellow, in various proportions. Thus, he claimed he could show by experiment that Newton's condition (many colours in equal proportions) was only *sufficient* for white light, but not *necessary*.[44]

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[42] Newton was clearly disappointed that Hooke had failed to recognise the epistemically special relationship between his new theory and his experiments (Newton, 1959-1977: Vol. 1, 171). For, instead of considering Newton's support for his theory, Hooke had discussed whether another hypothesis could fit the evidence just as well. However, it is useful to note that Newton misinterpreted Hooke's objection. Where Newton took Hooke to be attempting to assert his own hypothesis in place of Newton's, Hooke was in fact careful to point out that other hypotheses could also fit the facts (Newton, 1959-1977: Vol. 1, 113).

[43] It is worth noting that, while both Hooke and Huygens had stakes in the debate in that they both had recently published books concerning optics, they weren't threatened to the same extent by Newton's new theory. Huygens had developed a mathematical wave theory, which developed the notion of wave fronts, but which didn't deal with colour. In contrast, Hooke's wave theory offered a new modificationist account of colour. Hooke had more to lose.

[44] Although Huygens did admit that he hadn't tried this yet ("*car cette pensee ne m'est venue qu'a cette heure*" (Newton, 1959-1977: Vol. 1, 257, n.4)).

Newton dismissed the methodological argument. His pointed out firstly that fewer colours does not necessarily mean fewer, or simpler, explanations, and secondly that Huygens' two-colour model is not as simple as he thinks. While Newton's theory only needs to give *one* explanation of colour, Huygens' theory needs to give *two* (one to explain how light is coloured, and one to explain why there are only two primary colours). Newton concluded that, if ease of formulating an explanation were indeed a relevant concern, then surely it would speak in favour of *his* theory rather than Huygens'.

Newton's response to Huygens' empirical argument was two-pronged. On the first prong, he challenged the accuracy of Huygens' experiment. He suspected that Huygens had combined *compounds*, instead of *original colours*, to produce white (Newton, 1959-1977: Vol. 1, 265). Newton recommended therefore that, before combining the colours to make white, Huygens should try properly to separate the light into uncompounded colours. Only then, when he was certain he had original yellow and original blue *and no other colours*, should he try to make white out of them. On the second prong, while remaining sceptical that Huygens had managed to produce white from two original colours, Newton argued that, in any case, such an event would not refute his theory. For, if a white was produced out of original blue and original yellow, it wouldn't have the same properties as sunlight. This is because original blue and original yellow cannot separate into any other colours. Moreover, light is *still* composed of heterogeneous beams of varying colour and refrangibility, *even if* there is more than one way of creating visually similar compounds.[45]

Huygens' second objection concerned Newton's method of hypothesis-avoidance. He argued that Newton's theory was incomplete without a hypothesis. For, without a mechanical explanation of the nature of light and colours, Newton had not taught us about the nature and difference of colours, but only the accident ("*mais seulemt cet accident*") of their different refrangibility ("*de leur differente refrangibilité*" (Newton, 1959-1977: Vol. 1, 256)).

[45] Nevertheless, from then on, Newton was always careful to distinguish between sunlight and white light! See (e.g. Newton, 1952: 26, 63, 116).

Newton replied to this objection by clarifying the aims of his inquiry, and how these related to his distinction between *theories* and *hypotheses* (outlined in table 2 below).[46] This is a good opportunity to remind ourselves of how Newton thought of this distinction.

In Newton's methodology, theories and hypotheses deal with different subject matter, have different epistemic status and perform different roles in theorising. Theories systematise the observable, measurable properties of things; hypotheses describe the (unobservable) nature of things. Theories are inferred from observation and experiment; hypotheses are speculative. And so, Newton's claims about the composition of white light, and the thirteen propositions of his theory of colours, were theories; but his claims about the corpuscular nature of light were hypotheses.

Theory	**Hypothesis**
A proposition is a 'theory' iff it meets the following conditions: T1. It is certainly true, because it is reliably inferred from experiment; T2. It is experimental—something that has empirically *testable* consequences; and T3. It is concerned with the *observable, measurable properties* of the thing, rather than its nature.	A proposition is a 'hypothesis' iff it meets one or more of the following conditions: H1. It is, at best, only highly probable; or H2. It is a conjecture or speculation—something not based on empirical evidence; or H3. It is concerned with the nature of the thing, rather than its observable, measurable properties.

Table 2 Definitions of 'theory' and 'hypothesis'

The distinction between theories and hypotheses is central to Newton's methodology. For Newton, theories were on epistemically surer footing than hypotheses because they were grounded on phenomena, whereas the latter were grounded in speculations. And so hypotheses could never trump theories. When faced with a disagreement between a hypothesis and a theory (for instance, suppose our theory seems to imply action-at-a-distance, but the most plausible hypothesis about the nature of motion tells us that action-at-a-distance is impossible), we should modify the hypothesis to fit our theory, and not *vice*

[46] For a discussion of the distinction between theories and hypotheses in early modern philosophy more generally, see (Ducheyne, 2013).

versa. The distinction was nicely captured in a draft letter from Newton to Roger Cotes (March 1713):

> And therefore as I regard not hypotheses in explaining the phenomena of nature, so I regard them not in opposition to arguments founded upon phenomena by induction or to principles settled upon such arguments. In arguing for any principle or proposition from phenomena by induction, hypotheses are not to be considered. The argument holds good till some phenomenon can be produced against it (Newton, 2004: 120).

And so, while Newton railed against hypotheses (most (in)famously "*Hypotheses non fingo*")—determined to preserve the certainty of his propositions and to avoid epistemic loss by keeping speculative conjectures apart—hypotheses played an important role in Newton's negotiations between certainty and speculation.[47]

Huygens' demand that Newton provide a hypothesis—speculate about the underlying nature of light—then, clashed directly with Newton's methodological commitment to providing theories rather than hypotheses. Having said this, Newton was perhaps sensitive to the need for a theory to be at least *possible,* and this may explain his decision to develop and publish the much more speculative corpuscular hypothesis in 1675.

4.3 Newton's Research Programme

Newton's responses to Hooke and Huygens reveal some of the important—perhaps revolutionary—features of his method and his research program. Where Hooke presupposed a certain uniformity in light, and this coloured (if I may) his interpretation of experimental results, Newton strove to keep his speculations and his phenomena distinct. Where Huygens appealed to explanatory virtues and saw a crucial role for speculative hypotheses, Newton instead focused on what could be mathematically stated about the phenomena.

These features, as well as Newton's careful concern for experimental precision, reflect Newton's overall aim of certainty. By establishing a new property of sunlight (i.e. its heterogeneity) beyond reasonable doubt via experiment, as Newton claimed to have done

[47] For an extended discussion of the respective roles of hypotheses and queries in Newton's natural philosophy, see (Walsh, 2014).

with his *experimentum crucis*, and by inferring a theory of light from that property, Newton created a geometric, precise and systematised science of colour. Such a programme treats metaphysical speculation about the nature of things as secondary—even when Newton did publish his 'Hypothesis', he intended it to be a possibility proof of his theory. This disdain for speculation is, perhaps, reflected as well in his aesthetic/perceptual emphasis on ROYBGIV. For Newton, the so-called 'primary colours' are not privileged due to the nature of light (after all if indeed he wanted to argue such a thing, he would have needed some way of proving it) but due to contingent features of human experience.

Newton's early optical work, then, was not only revolutionary for what it told us about light and colour. It was also a fine example of the *methodological* innovations which Newton bought to the early modern table.

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