Logique & Analyse **194** (2006), 199–223

OPTICAL VERSUS MECHANICAL MODELS: NEWTON’S FAILURE TO CONSTRUCT A SATISFACTORY THEORY OF THE PHENOMENA OF LIGHT AND COLOUR

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Abstract
In this essay, I take up both Shapiro’s and Hakfoort’s suggestion that Newton tried to apply the same method he used in the *Principia* (first edition: 1687) to *The Opticks* (first edition: 1704). Why did Newton’s method, which was apparently so successful in the realm of mechanics, fail when applied to optics? I shall argue that both empirical as well as methodological aspects are needed to explain Newton’s failure. Newton’s repugnance to introduce hypotheses in published texts forced him to explore, in the demonstrative part of science, a conceptually poor framework. Such framework has limited inferential power, i.e. the set of consequences which can be deduced from it is limited. This will be contrasted with the *Principia* where a richer conceptual framework was at hand and its deduced effects could by confirmed by experiment. The conceptual framework in the *Principia* allowed Newton to *a priori* deduce the celestial motions. As I have argued elsewhere, *a priori* deducing the phenomena under investigation was one of Newton’s most central methodological ideals. In this essay, I shall attempt to explain why *a priori* deduction of phenomena was impossible in optics.

1. *Introduction*

In this paper it is my aim to investigate some of the differences between the *Principia* and *The Opticks*. Contrary to the *Principia*, Newton conceived of *The Opticks* as an imperfect work. In a recent article, I. Bernard Cohen concluded that:

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> Additionally, the omission of the author's name, like the choice of English rather than Latin as the language of the text, would seem to be a kind of admission by Newton of the imperfect or incomplete nature of the *Opticks* and was to some degree an echo of the failure to produce a mathematical treatise or at least on optics based on mathematical principles. (Cohen, 2001, p. 41)

Newton was quite reluctant to publish his optical work. His optical endeavours were left incomplete.[1] In this paper, I shall explain in more detail why Newton's mathematical method was so successful in mechanics, but not quite so in the area of optics. My focus here is on the differences between the conceptual frameworks in Newton's optics and mechanics, and their "conceptual richness". A conceptually rich framework allows for more inferences than a conceptually poor framework (and hence, has a lot of inferential power). Whether a conceptual framework is rich or not will depend on both empirical limitations as well as methodological choices.

Let us begin by reviewing how scholars have perceived the difference(s) between Newton's optical work and his mechanical work. I. Bernard Cohen claimed that the essential difference between *The Opticks* and the *Principia* is that the former proceeds analytically, i.e. by making experiments and observations and drawing general conclusions from them by induction, and the latter synthetically, i.e. proceeding from the discovered causes (Cohen, 1956, p. 192).[2] This seems to suggest that both works contained a different methodology (Cohen, 1980, pp. 134–135). Indeed in his *Newtonian Revolution*, Cohen wrote:

[1] In the Advertisement of the 1704 edition of *The Opticks*, Newton wrote: 'I have here publish'd what I think proper to come abroad, wishing that it may not be translated into another language without my consent' (Newton, 1979, p. cxxi). In the section just before the Queries Newton, wrote: 'And since I have not finish'd this part of my Design, I shall conclude with proposing only some Queries, in order to a farther search to be made by other.' (ibid., p. 339).

[2] Cohen's distinction is clearly mitigated by the fact that Newton himself pointed out that both the *Principia* and *The Opticks* contained analytical and synthetic movements. In the first eight propositions of Book III of the *Principia*, Newton established that the motions of the primary and secondary planets are caused by gravity. Hereafter, he showed that the irregular motion of the Moon, the tides, the motion of comets, and the oblate form of the Earth, can also be explained by the cause of gravity (Newton, 1999, p. 382). In *The Opticks* Newton demonstrated the heterogeneity of white light on the basis of several prismatic experiments. Hereafter, he showed that other phenomena, such as the rainbow, can be explained by the heterogeneity of white light (Newton, 1979, p. 405).

> More significantly, the propositions are not proved by the application of mathematical techniques. Rather Newton must often proceed by giving 'PROOF by Experiment', and he tends to refer back to previous experiments rather than to the preliminary axioms. Hence, although Newton uses numbers (as in the results of experiments), his *Opticks* can in no legitimate sense be considered a mathematical treatise. Another way of stating this conclusion is that in the *Opticks* Newton does not proceed by using what I have been calling the Newtonian Style. (Cohen, 1980, pp. 134–135, cf. p. 136, p. 141)

Recent authors have correctly tempered such claims: Newton tried to apply the same method so successful in mechanics to optical phenomena, but failed. Alan E. Shapiro stresses the phenomenal character of Newton's optical work and sees links with Cohen's "Newtonian style" (Shapiro, 1993, pp. 22–23). According to Shapiro, Newton restricted himself to experimentally observed properties without any reference to causal explanations (ibid.). Caspar Hakfoort similarly argued that Newton attempted to proceed in *The Opticks* in the same way as he did in the *Principia*, i.e. by his descriptive (and hence anti-causal (Hakfoort, 1988, p. 104)) Newtonian style[3], but that this method was less effective in optics (Hakfoort, 1988, p. 109). Note that Hakfoort and Shapiro[4] seem to suppose that the "Newtonian Style" is necessarily non-causal. Ernan V. McMullin also claims that Cohen's account precludes abductive reasoning (McMullin 2001, p. 289). However, I. Bernard Cohen explicitly stated (in commenting on Propositions 1–3, Book I) that Newton was able to demonstrate that a mathematically descriptive law of motion was shown by mathematics to be equivalent to a set of causal conditions of forces and motions (Cohen 1980, p. 28, p. 37). This leaves room for causal knowledge and abduction (see especially Smith, 2002). What is important for our present purposes — leaving aside the disagreement amongst scholars on the implications of the "Newtonian Style" — is that Hakfoort nor Shapiro did comment much on *why* Newton's mathematical method was ineffective in

[3] Hakfoort stays very close to Cohen's description of the "Newtonian Style" (Cohen, 1980, pp. 61–68). Hakfoort summarizes I. Bernard Cohen's "Newtonian Style" as follows: 'In the first place an imaginary 'mathematical construct' (Cohen's term) is investigated mathematically. (...) In phase 2 the construct is confronted with experiments, observations and mathematical laws which have an empirical backing, e.g. Kepler's area law. As a result of this, a second, more complicated, construct is studied in a new phase 1.' (Hakfoort, 1988, p. 103).

[4] However, as we shall see in section 6, Shapiro made some interesting suggestions on Newton's failure in optics.

optics. The precise reasons for this failure need to be rendered more explicit. This is the issue at stake.

Let me first add some remarks on the nature of Newton's failure in optics. I. Bernard Cohen has pointed out three reasons why Newton remained unsatisfied with *The Opticks*: (1) he had not been successful in his study of diffraction (see also Shapiro, 2002, p. 250; Shapiro, 2000b, p. 63, p. 70), (2) the book ended with a considerable list of unanswered *Queries*, and (3) he failed to construct a mathematical theory on par with the physics in the *Principia* (Cohen, 2001, pp. 18–23). These types of failure should be clearly distinguished from the famous failure of Newton to assign a further cause to gravity (Newton, 1999, p. 943). In the *Scholium Generale* added to the second edition of the *Principia*, Newton grants that he has explained the planetary motions by the proximate cause of gravity, but that he did not succeed in deducing from experiments their remote cause, i.e. the cause of the proximate cause, gravity. In the *Principia*, however, Newton succeeded in constructing mathematical abductive "inference tickets" (Smith, 2002), i.e. propositions that allow one to infer from an observed mathematical regularity (i.e., the effects) the corresponding physical system (i.e., the cause) producing these regularities. In other words, he had developed a theoretical machinery that allowed him to proceed from effect to causes directly. This surely was no failure. In *The Opticks* Newton did not have such theoretical machinery at his disposal: for instance, the inference to the cause of prismatic phenomena (i.e., the heterogeneity of white light) is established by a contiguity argument, not directly by abductive inference tickets.[5]

The problem then is to first clarify Newton's method in the *Principia*. Correspondingly, in section 2, I shall briefly describe Newton's method in the *Principia* — this presentation of Newton's method is mainly based on Ducheyne, 2005a. In section 3, I shall show that the conceptual framework in *The Opticks*, contrary to the highly theoretical framework in the *Principia*, is essentially descriptive and phenomenological. To avoid confusion, it should be stressed that this observation alone does not explain Newton's failure in optics. Comparing the frameworks of *The Opticks* and the *Principia* is a way of setting the stage for sections 4–6, in which Newton's failure will be

[5] Based on the *experimentum crucis*, Newton could indeed understandingly claim that to every colour there corresponds a specific degree of refrangibility, but not that white light *is* a heterogeneous aggregate. Newton simply presupposed that the colours are never created but only separated (Shapiro, 1993, p. 11). Compare with: 'And that all such reflected Light is of the same Nature with the Sun's Light before its Incidence on the Base of the Prism, no Man ever doubted; it being generally allowed, that Light by such Reflections suffers no Alteration in its Modifications and Properties. (...) So then, the Sun's incident Light being of the same Temper and Constitution with his emergent Light, and the last being compounded of Rays differently refrangible, the first must be in like manner compounded.' (Newton, 1979, pp. 55–56).

explained. The descriptive character of *The Opticks* stems from the fact that Newton never wished to introduce unwarranted hypothetical elements on the nature of light and colours (at least in the demonstrative part of natural philosophy) (Shapiro, 1993, pp. 12–40). Newton's demonstrative ideal was to deductively infer the observed phenomena from a set of certain (and hence, non-hypothetical) principles (Ducheyne, 2005a). Newton's methodological ideal went hand in hand with anti-hypotheticalism. Given my approach, I will rephrase the original question into: *Why did Newton manage to create a rich framework without feigning hypotheses in the Principia, but not in The Opticks*? As I have briefly mentioned above, an essential feature of the *Principia* is that Newton was able to generate "inference-tickets" that allow one to infer the proximate cause, i.e. centripetal forces, from certain motions (*in casu*, Keplerian movement).[6] This is because in the *Principia* there are links between cause and effect (*via* the second law). In *The Opticks* such links would be possible only if one makes assumptions on the nature of light (e.g. a corpuscular view). In the *Principia* this doesn't cause any major problems: that the constituents of natural bodies are similar as the natural bodies they constitute (because they share the theoretically relevant property of "mass") is a quite uncontroversial claim (see section 6). Newton always eschewed from the endorsement of unwarranted hypotheses. It is better to have an unfinished but certain theory than a "rich", but only probable theory. As the reader has by now understood, I will focus on Newton's conceptual framework in optics. However, this cannot be isolated from the empirical problems Newton encountered in his optical works. I will take up some of these empirical problems in section 4. This will pave for section 5, in which I discuss the relation between the empirical and methodological aspect of Newton's failure. In the section 6, I will show how my account is an addition to Shapiro's insight that Newton's failure in optics is highly related to the failure of the method of "transduction".

2. *Models in the* Principia

One point should be stressed from the outset. My claims about Newton's methodology are restricted to the presentational sequence of Newton's theory (the method of justification) and do not pertain to the chronological sequence of the theory (the method of discovery).[7] When I use 'method' in

[6] Newton conceived of Keplerian movement as a *phenomenon*, i.e. as an inductive generalization from specific observations.

[7] A very helpful anonymous referee pointed out that Cohen's account was not only meant to explain Newton's actual texts, but that it was also intended to say something about Newton's actual practice. To my opinion, the early and the late Cohen seem to differ somewhat

this paper, I only refer to Newton's method of justification. There is surely no guarantee that the sequence presented in the *Principia* represents Newton's original train of thought that led to the theory.[8] With 'method' I refer to the way(s) in which scientific statements are proved and presented in a published text.

Let us look then at Newton's method in the *Principia*. George E. Smith stresses that the approximative propositions in the *Principia* are rigidly deduced from the laws and definitions of motion. In other words, the "*quam proxime*" inferences are backed-up by the deductions from the laws and definitions of motion (Smith, 2002, pp. 152–167). In the *Principia* Newton succeeded in deducing certain idealized motions (which correspond to the observed celestial motions) from his 3 laws of motion and his 8 definitions. The models[9] of Book I show that in certain *idealized* and *abstracted* situations, where the same laws of nature hold as in our world and where the same theoretical concepts are apt to describe phenomena, *perturbations* will occur. In other words, Newton is able to show that already in the more complex models (many-body systems) perturbations from strict Keplerian motion will

on this matter. Whereas the early Cohen perceived his account of the "Newtonian Style" as relevant for describing both the moment of justification as well as some aspects of the moment of discovery (e.g. Cohen, 1980, p. 65), the late Cohen seemed to stress that the "Newtonian Style" is limited to the moment of justification. In his introduction to Newton, 1999, Cohen wrote the following: 'In the *Principia*, Newton adopted *a mode of presentation* that enabled him to put aside, for the moment at least, any considerations other than those directly related to mathematics and mathematical conceptions of physics. I have called this *manner of composing the Principia* the "Newtonian Style," and have shown how it describes *Newton's procedure in developing the propositions of the Principia* and then applying them to the world of experiment and observation.' (Newton, 1999, p. 60; emphasis added).

[8] As far as the method of justification is concerned, Newton preferred a *unified way* of demonstrating in natural philosophy by using a double method consisting of: *analysis*, in which causes are established, followed by *synthesis*, in which we assume the causes discovered and explain other phenomena (Newton, 1979, pp. 404–405; Newton, 1999, p. 382, p. 415). Fragments like these suggest that Newton favoured one method, and accordingly tried to apply it. This does not preclude that in the method of discovery Newton's method was more diverse and open to the introduction of hypotheses (however, in the demonstrative part of science hypotheses had to be banned). For numerous examples of optical hypotheses that were suppressed in the moment of justification, see Shapiro 1993. In any case, Newton's ideal should be critically compared with his practice.

[9] Models are understood here as "the primary representational entities in science" (Giere, 1999, p. 5). Models are the entities scientists employ to represent a natural system. Models can be very broadly conceived: we can think of computer models, scale-models and mathematical models. Newton's models clearly subsume under the class of mathematical models. In what follows I shall briefly point to the "constituents" of the Newtonian models.

occur. Let me illustrate this with an example from the *Principia*. In Proposition 65, Book I, Newton shows that in certain many-body system (see *infra*) in which each body exerts an inverse-square force on all other bodies, the deviations from Kepler's second law will only be minor and these bodies will nearly describe ellipses (keep in mind that such systems presuppose point masses and *in vacuo* movement):

> More than two bodies whose forces decrease as the squares of the distances from their centers are able to move with respect to one another in ellipses and, by radii drawn to the foci, are able to describe areas proportional to the times very nearly. (ibid., p. 568)

Newton shows that perturbations will occur from Kepler's first and second law in such complex idealized and abstracted cases. Next he proves this for two simple cases[10] these perturbations will be negligible: (1) for several lesser bodies revolving around a greater one at various distances (this can later be used for the primary planets), and, (2) for several smaller bodies revolving in the way described around a greater body, or any system of two bodies revolving around each other, to be moving uniformly straight forward and at the same time to be urged sideways by the force of another very much greater body situated at a great distance (this can later be used for the secondary planets).[11] In the first case these bodies will describe areas proportional to the times insofar as errors introduced either by the departure from the greater body from that common centre of gravity or by the mutual interactions between the lesser bodies are neglected (ibid., p. 568). In the second case, the several smaller bodies revolving around the greater body can be conceived as one body, "because of the slight distance of those parts from one another". This will only give rise to small errors produced by the distances between the parts (ibid., p. 569).

These models are constructed independently, i.e. as an investigation which motions will be produced by certain force functions. Newton does not from the beginning focus on the kinds of forces that are present in nature. Therefore, these models can be considered to have a stronger explanatory power, since they are directly deduced from the principles of motion. Unless the

[10] This, as Newton adds, can be extended for more complex cases indefinitely.

[11] He further writes: 'The more the law of force departs from the law there supposed [i.e. the inverse square law], the more the bodies will perturb their mutual motions; nor can it happen that bodies will move exactly in ellipses while attracting one another according to the law here supposed, except by maintaining a fixed proportion of distances one from another. In the following cases, however, the orbits will not be very different from ellipses.' (Newton, 1999, p. 568).

deductions are false or the laws and definitions of motions are wrong, this model explains the deviations in the real world. This backing-up procedure is an essential feature of Newtonian methodology. Moreover, some propositions allow one to calculate the perturbation factor (e.g. Propositions 45 and 60). These propositions express what Harper has called "systematic dependencies" (which differentiate Newton's way of modelling from a strictly hypothetical-deductive account) (Harper, 1990). Newton was able to predict these perturbations and to explain them. Put differently, he was able to account for the discrepancies between the first simple models and the observed phenomena by means of more subtle models. *A priori* deduction of phenomena was intertwined with methodological validity.[12] In the *scholium* following section 11 of Book I, Newton wrote on his method:

> Mathematics requires an investigation of those quantities of forces and their proportions that follow from any conditions that may be presupposed. Then, coming down to physics, these proportions must be compared with the phenomena, so that it may be found out which conditions [or laws] of forces apply to each kind of attracting bodies. And then, finally it will be possible to argue more securely concerning the physical species, physical causes, and physical proportions of these forces. (Newton, 1999, pp. 588–589)

In the first stage, Newton investigated the mathematical properties that follow from a specified physical system. In the second stage, he investigated the *observed* mathematical properties in order to establish the physical system producing these mathematical properties. In other words, Newton abductively inferred the forces in nature (see Ducheyne, 2005a, p. 14; see also Ducheyne, 2005b, in which I argue that Newton's method is inspired by the

[12] John Worrall argues that Newton's argument for the heterogeneity of white light is (at least at first sight) different from a hypothetico-deductive approach. Whereas a H-D approach starts with the theory and proceeds by investigating the observational consequences, in Newton's method the theory (heterogeneity of light) is the conclusion of an argument that begins with observational premises (prism experiments) (Worrall, 2000, pp. 64–65). This agrees very well with the *Principia*.

tradition of *regressus*[13]). In the third, optional, stage it will be possible to ascertain the physical causes of these forces.

In Ducheyne (2005a), I have argued that there are at least three constituents (sets) of Newton's models in the *Principia*:

(1) *an "ontological" set*: a set of fundamental "entities", i.e. point masses, "empty" points, and forces, which constitute one-body-systems, two-body-systems, three-body-systems or many-body-systems *in vacuo*,
(2) *a nomological and theoretical-conceptual set*: a set of laws and definitions (3 laws and 8 definitions), and finally,
(3) *a mathematical set*: a mathematical description of these entities and operations upon them.

(2) and (3) constitute the *inferential framework* that allows Newton to generate information from (1). All propositions in Book I of the *Principia*, follow by deduction from the laws and definitions of motion, and some mathematical operations (e.g. Euclidean geometry, Newton's method of "ultimate ratios"). These propositions or models function as inference-tickets. As we have just seen, some of the more complex models (e.g. Proposition 65) predict that under certain constellations small deviations from Kepler's area law will occur. This was, I think, the more secure method Newton had in mind. Newton was able to produce highly ingenious inference-tickets, which were based on deduction from the three sets, to infer inverse-square centripetal forces. The conceptual apparatus in the *Principia* is crucial: it enabled Newton to generate mechanical models from it. That is not to say that empirical data were unimportant. Deciding whether a model is empirically adequate or that the deviation predicted by gravitational theory agrees to an observed

[13] This Aristotelian textbook tradition of *regressus* was one of the sole traditions which perceived scientific reasoning as a dual process of proceeding from effects to causes and then from causes back to effect. Newton recast his innovating scientific demonstrations in an Aristotelian terminology. See Ducheyne, 2005b, for the details. Dear correctly notes that Newton was also highly indebted to the Barrovian programme of physico-mathematics (Dear, 1995, p. 213, pp. 224–226). Newton's method therefore seems to be a marriage between the *regressus* tradition and the tradition of what Peter Dear calls physico-mathematics (ibid.). See especially Chapter 8 entitled "Barrow, Newton, and Constructivist Experiment". The *regressus* tradition is required to explain Newton's causal stance on scientific explanation; the tradition of physico-mathematics is required to explain the abstract mathematics.

deviation is not an easy matter: it supposes countless experimentation, calculation and numerous ways of figuring out how to make things calculable in the first place.[14]

3. *The Conceptual Framework in* The Opticks *and the* Principia

I shall now compare the conceptual frameworks of *The Opticks* and the *Principia*. Let us look at the definitions and axioms which constitute the conceptual framework of *The Opticks*. They are premised in order to explain the properties of light by reason and experiment, and not by hypotheses (Newton, 1979, p. 1). First in line is Newton's famous definition of rays of light:

> *By the Rays of Light I understand its least Parts, and those as well Successive in the same Lines, as contemporary in several Lines.* For it is manifest that Light consists of Parts, both Successive and Contemporary; because in the same place you may stop that which comes one moment, and let pass that which comes presently after; and in the same time you may stop it in anyone place, and let it pass in my other. For that part of Light which is stopp'd cannot be the same with that which is let pass. The least Light or part of Light, which may be stopp'd alone without the rest of the Light, or propagated alone, or do or suffer any thing alone, which the rest of the Light doth not or suffers not, I call a Ray of Light. (ibid., pp. 1–2)

The meaning of this proposition has often been discussed. Newton explicitly held that both emission theories and wave theories of light were compatible with his definition (Turnbull, 1975, I, p. 175, see also Sabra, 1967, p. 274; Laymon, 1978, p. 61). Newton presupposed that light consists of discrete parts (*not* particles). That aspect is compatible with e.g. Hooke's wave theory.[15] Note that the first definition implicitly assumes that the rectilinear

[14] I grant it that my proposal in Ducheyne, 2005a concentrates on the moment of model construction and to a lesser extent on the moment of model testing. Both are required to establish a full account of Newton's methodology.

[15] Abdelhamid I. Sabra mistakenly claims that there is no difference between Newton's (constructive) doctrine of light and the corpuscular theory (Sabra, 1967, p. 284). He claims that Newton's rays were always those of the corpuscular theory: A wave interpretation was denied *a priori* (ibid., p. 288). Alan E. Shapiro notes that this definition is incompatible with diffusion theories of light, which assume that individual rays are not physically independent, not with wave theories in general (Shapiro, 1975). Ronald Laymon correctly criticises Shapiro's interpretation since it entails that the *experimentum crucis* is apparently not a fair test of diffusion theories. Laymon claims that Newton's definition of a ray of light is not incompatible with diffusion theories, since Hooke allowed (as Hobbes did) the width of a

propagation of light and the independence of rays. What is important is that Newton considered the first definition as a *phenomenological statement* according to which "every part of a beam of light is refracted and reflected according to a regular law independently of any other part of the beam of light", as Shapiro has argued (Shapiro, 1975, p. 196). After Newton's first definition, the definitions of refrangibility, i.e. the disposition of rays of light to be refracted, and reflexivity, i.e. their disposition to be reflected, follow (ibid., pp. 2–3). Next in line, are the definitions of the angle of incidence, reflection and refraction (ibid., p. 3). From these definitions, the definitions of the sines of incidence, reflection and refraction follow. Finally, homogeneal or primary light is defined: rays that have the same angle of refraction (ibid., p. 4). These definitions are mainly *terminological* and *phenomenological*. In great contrast to the *Principia*, the definitions did not refer to the causal agents or forces (impressed force and centripetal force (as a subclass of impressed forces)) producing motions. Rather, they define the crucial terms in the study of optics.

After these eight definitions, eight axioms follow. The first axiom states that the angles of reflection and refraction lie in the same plan with the angle of incidence (ibid., p. 5). The second that the angle of reflection is equal to the angle of incidence (ibid.). The third that if a refracted ray is returned to the point of incidence that it will be refracted into the initial line by the incident ray (ibid.). This suffices to give the reader an idea of the nature of these axioms.[16] In these axioms, the *geometrical properties* of the central concepts of optics (defined previously) are presented. These axioms mainly refer to the angles formed between the incident and outgoing rays before and after reflection or refraction.

ray to become smaller than "any given magnitude" to deal with refraction in curved surfaces (Laymon, 1978, p. 65). In this case, the rays are independent of each other. I side with Laymon here.

[16] The fourth states that when a ray is refracted from a rarer into a denser medium, that the angle of refraction is less than the angle of incidence (ibid.). The fifth that the sine law holds "either accurately or very nearly" (ibid.) (see 4.1). The sixth that homogeneal rays which flow from several points of any object, and fall perpendicularly or almost perpendicularly on any reflecting or refracting plane or spherical surface, will afterwards diverge from so many other points, or be parallel to so many other lines, or converge to so many other points, either accurately or without any sensible error (ibid., p. 10). The seventh that the rays which come from several points of an object meet again in so many points after they lave been made to converge by reflection or refraction, will make a picture of the object upon any white body (ibid., p. 14). The eighth that an object seen by reflexion or refraction, appears in that place from whence the rays after their last reflexion or refraction diverge in falling on the spectator's eye (ibid., p. 18).

This conceptual framework is essentially descriptive, geometrical and phenomenological. The axioms express geometrical regularities. The definitions are mostly stipulative definitions (for instance, they define the angle of incidence). As we will see shortly, *The Opticks* did not allow for a conceptual framework that would allow to relate the effects observed to the causes producing them. When we compare this with the *Principia* the difference is striking. Its tenor is vastly more theoretical and conceptually rich. Let me clarify what I mean with that. The framework in the *Principia* presupposes causal knowledge about the world: forces cause change in motion and bodies have inherent forces. Forces are not directly accessible (therefore "theoretical"[17]) to us and they are only known by their effects. The laws of motion clearly make reference to such knowledge:

> Law 1:
> Every body perseveres in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change it state by forces impressed.
> Law 2:
> A change in motion is proportional to the motive force impressed and takes place along the straight line in which the force is impressed.
> Law 3:
> To any action there is always an opposite and equal reaction, in other words, the actions of two bodies upon each other are always equal and always opposite in direction. (Newton, 1999, pp. 416–417)

Bodies have inherent forces and they are potentially affected by impressed forces. Using these laws we can gain information about the magnitude and direction of the forces acting on a body. Then eight definitions follow. In the first quantity of matter is defined as a measure that arises from its density and volume jointly (Newton, 1999, p. 403). In the second quantity of motion is defined as a measure of motion that arises from the velocity and the quantity of matter jointly (ibid., p. 404). Definition three deals with inherent force of matter, i. e. the power of resisting by which every body, so far as it is able ("*quantum est in se*"), perseveres in its state either of resting or of moving uniformly straight forward (ibid.). Definition four defines impressed force as the action exerted on a body to change its state either of resting or of moving uniformly straight forward (ibid., p. 405). Definition five defines

[17] With "theoretical knowledge" I refer to knowledge which transgresses directly accessible empirical knowledge. I admit that the distinction is not clear-cut, but the intuitive characterisation is sufficient for my presentational purposes.

centripetal force as the force by which bodies are drawn from all sides, are impelled, or in any way tend, towards the some point as to a centre (ibid.). Definitions six, seven and eight deal with the absolute quantity of centripetal force, i.e. the measure of this force that is greater or less in proportion to the efficacy of the cause propagating it from a centre through the surrounding regions (ibid., p. 406), the accelerative motion of centripetal force, i.e. the measure of this force that is proportional to the velocity it generates in a given time (ibid., p. 407), and the motive quantity of a centripetal force, i.e. the measure of this force that is proportional to the motion it generates in a given time (ibid.). The conceptual framework in the *Principia* circles around the notion of force. Newton's definition of impressed force as changing the state of rest or uniform motion of a body is closely related to his metaphysical principle of causality (Jammer, 1957, p. 121). Since every change must have its cause, the change of motion is an effect and the impressed force its cause. This carries a lot of information with it. For instance, if we observe a body that does not describe a rectilinear path (as it tends to do by its inherent motion), we can infer that it is acted upon by an impressed force. In other words: Newton established a relation of counterfactual dependency between orbital motion and the forces producing them.[18] We can then try to determine its direction and strength, given the laws and definitions. The conceptual framework in the *Principia* allowed Newton to infer information about the proximate causes. In *The Opticks* no such thing is at hand. Why?

I take it then that the conceptual framework in the *Principia* is richer than in *The Opticks*, because there are links between the effects and the causes (*via* the second law).[19] The make-up of the affected entities (= the effects) is known. We know that the effects which we want to explain are material bodies moving along certain trajectories. This has nothing to do with the fact that the cause of gravity is unknown: in mechanics we know the make-up of what we want to explain (bodies *and* their constituents have the property of *mass*); in optics, by contrast, we do not know the make-up of optical phenomena (e.g. prismatic dispersion), because this would already presuppose an optical theory. We do not know the nature or constituents of colours. Are they bodies? This would surely be an interesting claim from an inferential

[18] William Whewell seems to have thought along similar lines in his *Philosophy of the Inductive Sciences*: '*Force is any cause which has motion, or change of motion, for its effect*; and thus, all the exchange of velocity of a body which can be referred to extraneous bodies, — as the air which surrounds it, or the support on which it rests, — is considered as the effect of forces; and this consideration is looked upon as explaining the difference between the motion which really takes place in the experiment, and that motion which, as the law asserts, would take place if the body were not acted on by any forces.' (Whewell, 1967 ,Vol. I, p. 217).

[19] In the last paragraphs of this section I am indebted to the highly insightful comments of an anonymous referee.

perspective. If the rays of light possibly be globular, they would be attracted by material bodies; furthermore, if they had different masses, they would be subjected to different deviations in function of their mass (Ronchi, 1970, pp. 162–163). In his early optical work, Newton tried to reduce the phenomena of light and colour solely to the size and density of its corpuscles (Shapiro, 1993, pp. 119–121). On this assumption, it is straightforward — as Newton attempted (see 4.1) — to attempt to demonstrate that refraction is caused by a centripetal force tending downwards along the normal. A framework in which light is considered as consisting of small bodies would be more inferentially rich: it would allow you to apply the known laws of bodies to the phenomena of light. Heuristically, Newton relied heavily on the hypothesis of light particles in a vibrating medium "to suggest and interpret experiments and to deduce the mathematical and physical properties of periodic colors" (Shapiro, 1993, p. 50, cf. p. 65). In the published result, all traces of these hypothetical elements were eliminated (ibid., p. 85, cf. p. 172). Newton always preferred to be silent on the nature of light and colours. It is better to leave unspecified what colour and light is. In doing so, he turned down the opportunity of publicly accepting a conceptually richer framework. This is the only apt attitude according to Newton's desire to construct a hypotheses-free science of optics. Newton's conceptual framework in *The Opticks* was less rich than in the *Principia*. The reason is that constructing a richer framework would entail making statements about the nature of light or colours, i.e. feigning hypothesis.[20]

According to Newton, a hypothesis is a proposition that is not a phenomenon, nor deduced from any phenomena but assumed or supposed without any experimental proof (Edleston, 1969, p. 155). In *The Opticks* Newton wrote that the main business of natural philosophy is 'to argue from Phaenomena without feigning Hypotheses, and to deduce Causes from Effects' (Newton, 1979, p. 369). Hence, according to my approach, 'hypothetical' means that its deduced effect cannot be confirmed by observation. Newton preferred to work with a less rich conceptual framework than to feign hypotheses. Cartesians started by boldly positing their causal explanations and tried to infer the required observational data from these (from theory to phenomena). Newton, on the contrary, preferred to begin with the phenomena and to infer the types of forces that produce these phenomena given the laws of motion (from phenomena to theory). Newton's framework in *The Opticks* was conceptually poor, because the deduced effects of a richer content could not

[20] As Hakfoort pointed out: 'But the identification of light rays with particles (as proposed in the Queries) entailed the use of a causal model. In short, Newton's critics as well as his defenders and indeed Newton himself, all agreed that using the concept of corpuscles of light was using causal model.' (Hakfoort, 1988, p. 107).

be confirmed by observation. In the *Lectiones Opticae* (1670–72)[21], Newton still believed in deducing the origin of colours from certain fundamental principles:

> But seeing that it is appropriate that I discuss in turn the measure of refractions in order to advance the science of optical instruments that perfect vision, and next many propositions are to be deduced upon which the origin of colors of this kind depends and must be explained, provided that I intended to *determine them solely from principles previously demonstrated (as is usual in geometry)*, it should not therefore displease you if I prepared some things about the laws of refractions and so interjected topics pertaining more to pure mathematics than those that concern physics. (Newton, 1984, p. 169; emphasis added)

Newton gradually abandoned the idea of *a priori* deducing the phenomena of light and colour. Transcending the mere phenomenological features of an optical phenomenon was at odds with Newton's obsession with certainty.[22] In conclusion: in *The Opticks* Newton could not publicly endorse a sufficiently rich framework from which the observed optical phenomena could be deduced without introducing hypothetical elements. But why could he not *a priori* deduce optical phenomena in the first place?

4. *Some Illustrations of Failure*

In this section, I shall discuss three difficulties Newton encountered in making a — to his own standards — proper optical science. Each example points to the problems Newton encountered in establishing his methodological ideal. The following three examples are problematic for Newton's attempt to construct an *a priori* model of optical phenomena: in his derivation

[21] Alan E. Shapiro notes the following differences between the *Lectiones* and *The Opticks* (Newton, 1984, pp. 23–25): (1) there is more emphasis given to the demonstration of the unequal refrangibility, to which Part I of *The Opticks* is dedicated and (2) the presentation of *The Opticks* is more formal (cf. the usage of definitions, axioms and propositions). In the *Lectiones*, Newton did not formally define a ray of light (ibid., p. 73n).

[22] The tenor of the *milieu* of the Royal Society was one of fallibilism, closely aligned to what Popkin has called "constructive scepticism" (Popkin, 1979). There was an intellectual clash between Newton's meta-scientific convictions and that of the fellows. For a fairly good picture of the Royal society milieu see van Leeuwen, 1963. I must warn the reader that I am not satisfied for his treatment of Newton's position on these matters. See Bechler, 1974 and Shapiro, 1985 with a better perspective.

of the law of refraction Newton had implicitly introduced the corpuscularity of light (see 4.1), the outcome of Newton's experiments on diffraction — a topic he started investigating in 1691 — cast doubt on the correctness of the principle of rectilinear propagation of light (see 4.2), and an early attempt of Newton to construct an *a priori* model of refraction failed (see 4.3). I shall begin with presenting the examples and, in section 5, I shall spell out some general reflections on the interaction between the empirical and methodological aspects of Newton's failure in optics. It will be shown that methodological and empirical aspects of Newton's failure can in practice hardly be separated.

4.1. *The Troubles with the Law of Refraction*

In the *Lectiones Opticae* Newton attempted to construct a mathematical theory of colour in which the refractions of rays of every colour in any medium could be deduced from a set of mathematical principles.[23] Newton only succeeded in deriving the law of refraction conditionally, i.e. by assuming some hypothetical forces.[24] Newton reduces real optical refraction to an imaginary situation.[25] Let us firstly find out what the assumptions are. In the Proposition 94, Book I of the *Principia* Newton is more explicit about the underlying assumptions. Newton assumes: (1) that the interface between two dissimilar media lies somewhere between two very near parallel planes[26], (2) that a ray

[23] Compare with: 'And the absolute certainty of a science cannot exceed the certainty of its principles. Now the evidence by which I asserted the propositions of colors is in the next words expressed from experiments, and so but physical: whence the propositions themselves can be esteemed no more than physical principles of a science. And if those principles be such that on them a mathematician may determine all phenomena of colors that can de caused by refraction and that by computing or demonstrating after what manner and how much those refractions do separate or mingle the rays in which several colors are originally inherent; I suppose the science of colors will be granted mathematical and as certain as any part of optics. And that this may be done I have good reason to believe because ever since I became first acquainted with theses principles, I have with constant success in the events made use of them for this purpose.' (Turnbull, 1975, I, p. 187).

[24] For a clear exposition of the proof see Sabra, 1967, pp. 305–308.

[25] Ronchi notes that: 'Strangely enough having gone so far he changed his method: he abandoned his original inductive-experimental reasoning, and instead deduced what the behaviour of prisms would have been according to the hypothesis: 'that bodies refract light by acting upon its rays in lines perpendicular to their surfaces'.' (Ronchi, 1970, p. 173). On my account this is not strange: Newton preferred *a priori* deduction.

[26] There is a small difference with the *Principia* here. In *The Opticks*, Newton assumes that the thinness of the terminated space is due to the fact that no sensible curvature of the rays' path is normally observed near refracting surfaces.

of light passing through the terminating planes suffers the same action as the particle, (3) that a body passing through this space is attracted or impelled perpendicularly toward either medium, (4) that this body is not acted on or impeded by any other force, and, (5) that the attraction is uniform (Newton, 1999, p. 622). In Proposition 6, Book I, of the *Opticks*, Newton used the same model but now he completely hid the physical interpretation. Commenting on this Proposition Newton stated:

> And this Demonstration being general, without determining what Light is, or by what kind of Force it is refracted, or assuming anything farther than that the refracting Body acts upon the Rays in Lines perpendicular to its Surface, I take to be a very convincing Argument for the full truth of this Proposition. (Newton, 1979, pp. 81–82)

Newton must have realised the problems with his treatment of refraction. Obviously, this model assumed atomism. Section 14, Book I of the *Principia*, is explicitly entitled "The motion of minimally small bodies that are acted on by centripetal forces tending towards each of the individual parts of some great body" (Newton, 1999, p. 622). Newton could not deliver any positive argument for that position. Therefore, the fundamental law of optics is based on hypotheses. This was unacceptable for Newton's rigid methodology.

4.2. *The Troubles with Diffraction*

Newton encountered serious troubles with diffraction (or as he called it, "inflexion") (see especially Shapiro, 2000). Diffraction is an interference phenomenon produced by the obstruction of a wave. He developed a model of diffraction based on the assumption that the path of the fringes (or, dark intervals) are identical or coincide with the rectilinear paths of the rays that produced them. Shapiro recently showed that Newton never expounded his linear-propagation model, since it was a hypothesis which was not derived from phenomena (Shapiro, 1993, p. 63; cf. Shapiro, 2000a, p. 43). As if that were not bad enough, Newton was forced to conclude — and thus contradicting his own basic principle — that the light which makes the fringes is different from that which is initially inflected (Newton, 1979, p. 332). In an experiment probably dating from 1692, Newton examines the diffraction pattern of light coming trough a small passage produced by two knives making a small angle with each other in order to form a V. He measured the distance between the knife-edges when the intersection of the first dark lines fell on a white paper placed at different distances from the knives (Shapiro, 2000b,

p. 65). These measurements showed that the light forming the same fringe, when it is observed at different distances from the knives, comes from different distances from the edges and is deflected at different angles (ibid., p. 66; Shapiro, 2000, pp. 30–32). Since light is supposed to be propagated rectilinearly, after it has passed through the blades, it cannot be the same light that forms the fringes at different places, i.e. the fringes do not propagate rectilinearly.[27] Newton tried to construct a linear model of diffraction, in which diffracted rays diverge from a common point of intersection (Shapiro, 2000a, p. 48). His model of diffraction that assumed "that the paths of the fringes were identical to or coincide with the rectilinear paths of the rays that produce them" (Shapiro, 2000a, p. 29, cf. p. 32, pp. 34–35). Obviously, this experiment forced him to question the rectilinear motion of light, one of his most basic and seemingly innocent assumptions. His basic optical axiom, the rectilinearity of rays of light and colour was hereby cast in doubt.

4.3. *An Early Attempt at an* a priori *Model of Refraction*

In an unpublished manuscript (U.L.C. Add. 3970, ff. 433r–444v), Newton tried to make an *a priori* model of refraction (Bechler, 1974). The "experiment" consisted in letting an uncoloured ray pass through a prismatic box ABC made of polished plates of glass cemented together at the edges, which is filled with water. In the box another prism DEF made of glass or crystal is placed upside down — so that the vertex of DEF points to the base of ABC. The bases of ABC and DEF are parallel to each other. The only relevant data that enter the scene are the refractive indices and dispersive powers of glass, water and air. Once these are known the rest follows without further experimentation. The model predicted that, given equal contrary refractive indexes, colours would appear and, if the refractive index of the interior prism is less than that of the exterior one, no colours will appear. Bechler notes that "it might well have been wholly thought-experiment" (Bechler, 1974, p. 114). It appears that in his early optical work, Newton was (over)confident in the fact that nature would easily yield to his methodological ideal of deducing of the refractive phenomena using only refractive indexes and some basic mathematical rules. The following statement is typical in that respect:

[27] In *Query 3*, Newton hypothesised 'Are not the Rays of Light in passing by the edges and sides of Bodies, bent several times backwards and forwards, with a motion like that of an Eel?' (Newton, 1979, p. 339). In *Query 28* Newton unluckily stated that 'Light is never known to follow crooked Passages nor to bend into the Shadow' (Newton, 1979, p. 363). This had lead Ronchi to state 'no one could have worked better than Newton, not to build, but rather to demolish, the corpuscular theory' (Ronchi, 1970, p. 191).

> Although I have not yet derived the certainty of this proposition [Newton's *a priori* dispersion law] from experiments, nevertheless I do not doubt that it will satisfy all of them which it is possible to do with that respect to it. (Newton, 1984, p. 201)

In a later version of the text the "experiment" from U.L.C. Add. 3970, ff. 433r–444v is missing. In *The Opticks* we encounter the same experiment (experiment 8, Part II, Book I) with only one significant difference: the empirical outcome was entirely the reverse as Newton's prior model predicted (Newton, 1979, pp. 129–130). Newton's attempt to an *a priori* dispersion model turned out quite unsuccessful.

5. *Empirical and Methodological Aspects of Newton's Failure in Optics*

The preceding examples seem to suggest that there are two types of failure in Newton's optics. Let us look at the first type. In 4.1, we have seen that Newton could not deduce the law of refraction from phenomena. He failed to accommodate his derivation of the law of refraction to his methodological ideal. In his mechanical work, Newton pointed to the similarity between refraction and centripetal forces. In the *Principia* (all editions), Newton noted that:

> These attractions are very similar to the reflections and refractions of light made according to a given ratio of secants, as Snel discovered, and consequently according to a given ratio of the sines, as Descartes set forth. (Newton, 1999, p. 625)

Somewhat further he granted that there is an analogy between the propagation of the rays of light and the motions of bodies:

> Therefore because of the analogy that exists between the propagation of rays of light and the motion of bodies, I have decided to subjoin the following propositions for optical uses, meanwhile not arguing at all about the nature of rays (that is, whether they are bodies or not), but only determining the trajectories of bodies, which are very similar to the trajectories of rays. (ibid., p. 626)

In *The Opticks*, Newton is silent about the analogy between the propagation of light and the motion of bodies. What explains Newton's silence? According to my interpretation, Newton increasingly became aware of the hypothetical nature of the derivation of the law of refraction, and had to suppress it in order to satisfy his own stringent methodological tenets. In *The Opticks* (1704), no physical interpretation of the demonstration of the law of refraction is given: its proof is given in *purely* mathematical terms (Newton, 1979, pp. 80–82). So in *The Opticks* Newton suppressed a perfectly tenable working-hypothesis, because it was not rigidly deduced from phenomena. This is one aspect of Newton's failure: the suppression of interesting working-hypotheses.

Let us look at the second type. In 4.2, we have seen how Newton's initial rectilinear model of diffraction was contradicted by experiments. Diffraction patterns defied one of Newton's seemingly innocent premises: the rectilinearity of light propagation. Notice that in the *Principia* Newton that light is "propagated along straight lines" (Newton, 1999, p. 776). These types of problems are empirical problems: phenomena defied Newton's assumptions. The example described in 4.3 seems to be derived from a combination of both empirical and methodological aspects.

The above examples show that Newton's methodological and empirical aspect of Newton's failure in optics can hardly be separated. *Because optical phenomena are so versatile and the constituents of light are unknown, Newton could not rigidly demonstrate the corresponding causes via a general theoretical principle (based on the nature of these constituents) which expressed a counterfactual relation between cause and effect. In addition to these empirical problems, Newton's method precluded publicly endorsing perfectly tenable working-hypotheses. This resulted in the suppression of several of Newton's explanations and ultimately in a very "poor" theory.* According to our contemporary understanding, light has a dual nature: under some circumstances it behaves particle-like (e.g. the Compton effect, the photoelectric effect), in others it behaves wave-like (especially during interference process such as diffraction). So ultimately, the reason that Newton could not empirically confirm the deduced effects of a richer conceptual framework has to do with the typical inscrutability and complexity (cf. its dual nature) of optical phenomena. Just consider the complexity of Newton's rings, a phenomenon that was clearly impossible to deduce from the principles of mechanics (Shapiro, 1993, p. 85). How should one explain this phenomenon, let alone deduce its cause from phenomena? Newton physically explained the rings by placing the cause at the second surface, where a particle and a wave interfered (ibid., p. 81). This is a perfectly legitimate working-hypothesis. Because it could not be rigidly deduced from some evident axioms, it was not good enough for Newton. He therefore refrained from this hypothesis in *The Opticks*. According to our contemporary explanation, Newton's rings are caused by the constructive (for the coloured rings) or destructive (for the dark rings) interference between the incident and reflected rays of light between a spherical and flat surface. It was only at the beginning of the nineteenth century that scientists began to realize that Newton's rings are compound (ibid., p. 83). These explanatory difficulties refer to empirical matters of fact that hampered Newton to create a mathematical science of optics. Furthermore, Newton preferred a very rigid ideal of scientific explanation that led him to suppress interesting working-hypotheses and made it even more difficult to endorse an inferentially rich theory of optics.

6. *Newton's Failure in Optics as a Failure of Transduction*

In this section, I shall show how my account is an addition to Alan E. Shapiro's work on Newton's optics. In his monumental study of Newton's optics (Shapiro, 1993), Shapiro concludes that Newton's method of transduction was "not up to the task of treating the colors of natural bodies" (ibid., p. 134). Shapiro has pointed out that Newton's failure in optics was due to the failure of the method of transduction *within* the domain of optics. Transduction refers to the method of making of inferences about the unobservable, *microscopic components* of bodies from the observed laws and properties of *macroscopic bodies* (Shapiro, 1993, pp. 4–5). In such an inference, we apply the observed macroscopic properties of bodies to their microscopic constituents. Without transduction, it would be impossible, according to Newton's own finding, to derive "the qualities of imperceptible bodies from the qualities of perceptible ones" (Newton quoted from ibid, p. 45). For instance, when arguing that opacity is produced by the parts of bodies, Newton uses *macroscopic* examples (Shapiro, 1993, p. 114). Similarly, in the early 1670s, Newton assumed that coloured bodies, consisting of absorbing primordial particles and pores, are produced by the highest order corpuscles in the same way as a fragment of a thin film (ibid., p. 113). Again, Newton illustrates his theory with a macroscopic example. This seems to suggest that in his early optical work Newton considered of the transduction of macroscopic properties to their microscopic constituents as unproblematic. The vulnerability of transduction lies in the following: justifying transduction for the properties of light and colour depends, as Shapiro puts it, on "the composition or hierarchical arrangement of the corpuscles that compose bodies" (ibid., p. 45). In fact, Newton began to see this weakness in the early 1690s (ibid., p. 46). This primordial methodological assumption was based on the simplicity or "analogy" of nature (ibid., p. 44). Obviously, this method presupposes that the components are of similar nature as the (macroscopic) bodies which they constitute.

I shall further illustrate by means of an example why the method of transduction was successful in mechanics. Let us see how Newton arrived at *universal* gravitation in Proposition 7, Book III. In the preceding propositions Newton has proved that all planets gravitate towards each other and that the gravity of each planet varies inversely as the square of the distance. It follows by proposition 69, Book I, that gravity towards all planets is proportional to their mass. Since all the parts of a planet A are heavy towards planet B, and since the gravity of each part to the gravity of the whole is as the matter of that part to the matter of the whole, and since to every action there is an equal reaction (by the third law of motion), it follows that planet B will gravitate in turn towards all the parts of A, and its gravity to any one part will be to its gravity toward the whole of the planet as the matter of that part to the matter of the whole (ibid., p. 811). Hence, the gravity towards the whole planet arises from and is compounded of the gravity of the individual parts (Corollary 1). From Corollary 3 to Proposition 74, Book I, it follows that the gravity toward each of the individual particles of a body is inversely as the squares of the distance of the places from those particles (Corollary 2). In mechanics, transduction is unproblematic because the constituents of bodies share the same theoretically relevant property with the bodies they constitute: namely, *mass*. In optics, by contrast, transduction is problematic because it amounts to asserting the corporality of light.

7. *Conclusion*

It has often been perceived that Newton favoured a non-hypothetical-deductive method (Ducheyne, 2005a; Harper, 1990; Sabra, 1967, p. 248; Worrall, 2000, p. 63). Arbitrary hypotheses must not be introduced. By contrast, Christiaan Huygens had no problems with this.[28] Newton preferred to demonstrate phenomena from some certain propositions — unluckily, it turned out that the fundamental principles in optics were uncertain. Hypotheses may be employed in the course of scientific inquiry, but they may not form part of asserted scientific doctrine (Sabra, 1981, p. 232; Shapiro, 1993, pp. 12–17). Newton tried to carefully separate hypotheses and demonstrated theories.

One of the disadvantages of this methodology is that one can only use established principles. Therefore, Newton's conceptual framework in his optical work stayed highly descriptive. Anything more theoretical would be equivalent with feigning hypotheses on the nature of light. A richer optical theory would have been too hypothetical for Newton to accept and publicly defend. It left his optical work in a sense uncompleted. Newton's failure in the optical domain can be explained by a combination of the following factors. The first reason has to do with Newton's idiosyncratic insistence

[28] For a clear view on the difference between Huygens's hypothetical-deductive method in *Traité de la Lumière* and Newton's work, see Shapiro, 1989.

on certainty which prevented him from exploring a more conceptually rich framework. The second has to do with specific empirical problems Newton encountered.

ACKNOWLEDGEMENTS

I would like to thank the two anonymous referees and Eric Schliesser for their most interesting and stimulating suggestions, criticisms and challenges.

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