UNDERDETERMINATION AND PROVABILITY. A REPLY TO OLAF MÜLLER

Timm Lampert

Newton claims to have proven the heterogeneity of light through his experimentum crucis. However, Olaf Müller has worked out in detail Goethe´s idea that one could likewise prove the heterogeneity of darkness by inverting Newton´s famous experiment (Mueller 2015a, 2016). Müller concludes that this invalidates Newton´s claim of proof. Yet, this conclusion only holds if the heterogeneity of light and darkness is logically incompatible. This paper shows that this is not the case. Instead, in Quine´s terms, we have two logically compatible theories based on mutually irreducible theoretical terms. From a Quinean point of view, this does no harm to the provability of the corresponding statements.

KEYWORDS: experimental proof; underdetermination; experimentum crucis; Newton; Quine

1. NEWTON´S EXPERIMENTAL PROOF

In the following, I will focus on Newton´s experimentum crucis or, as we will see, a part of it. I do so to discuss the validity and determinacy of Newton´s experimental proofs for presenting an argument that is as simple and strong as possible. The approach I take here will suffice for discussing the type of underdetermination in question and for arguing that underdetermination is compatible with provability. I will not be concerned with generalizing Newton´s method to a larger base of experimental data. Thus, I will only discuss weak underdetermination (the underdetermination of specific theories with respect to a confined set of data) and not strong underdetermination (the underdetermination of a universal theory with respect to all possible data).

Olaf Müller argues that Newton´s claim of experimental proof is mistaken because Newton´s conclusions are not determined by his experiments (Müller 2016, 326). Let us first analyse the type of underdetermination at stake and then discuss whether it is valid to conclude that Newton does not deliver proof.

One traditional approach to undermining Newton´s claim to have proven the heterogeneity of light through his experimentum crucis is based on analysing his proof as an argument to the best explanation, (cf., e.g., Layman 1978, 62f.; Sabra 1981, 249f.; Thompson 1994, 8f.). Such an argument begins from several alternative possible explanations (hypotheses) that are reduced based on experimental data. The critique of Newton´s claim then relies on standard arguments against this type of reasoning: (i) one can never be sure that the alternatives in question are complete, and (ii) it is always possible to reconcile experimental data and hypotheses using auxiliary assumptions. To sum up, Newton´s conclusion is not proven because his explanation is not determined by his experiment but rather is, at best, compatible with it.

This critique does not do justice to Newton´s proof. Newton has already insisted to Hooke that his conclusion is not `an Hypothesis but most rigid consequence, not conjectured by barely inferring `tis thus because not otherwise or because it satisfies all phaenomena […] but evinced by ye mediation of experiments concluding directly´ (Turnbull 1959, 96f.). As we will see in the following, Newton´s description of his method of argumentation can be substantiated. Thus, one should not base the debate regarding underdetermination and Newton´s proof on an analysis in terms of arguments to the best explanation. Indeed, this would reduce the debate to rather trivial points. In section 2, I will show that Müller´s analysis does not depend on such a misunderstanding of Newton´s proof but rather reveals a more interesting type of underdetermination. However, let us first confirm Newton´s claim that he begins his proof from experiments and ends with a proposition explaining the experimental data.

When describing Newton´s experimentum crucis verbally, as done by Newton (1672, 3078f.), or through a diagram, as done in Figure 1, it is impossible to abstain from invoking the concept of a ray. As we will see, this concept is crucial to our discussion. However, for now, let us simply adhere to Newton´s conventions and describe his experiment on the basis of rays emitted from the sun.

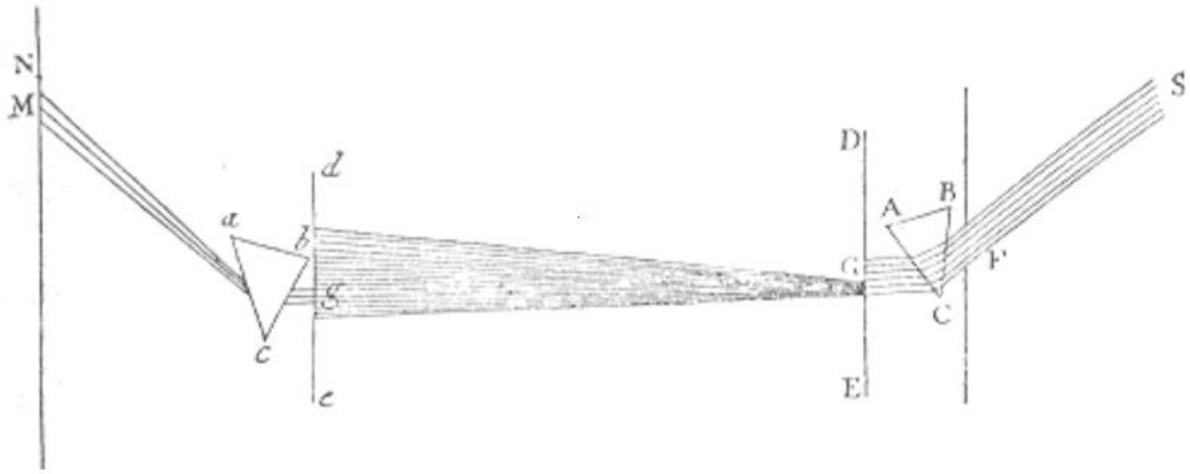

Figure 1. Newton´s Experimentum Crucis, taken from Newton (1931, Fig. 18)

The use of two prisms is essential to Newton´s experimentum crucis. The first prism induces a spectrum. With his experimentum crucis, Newton wishes to explain the length of this spectrum.[1] To achieve this goal, he selects rays from different parts of the spectrum by turning the first prism such that different rays fall on the second prism. As a result of this experimental method of separating the rays, the different rays strike the second prism `without any respect to a difference in their incidence´ (Newton 1672, 3079). This point is

[1] Cf. his conclusion in Newton (1672, 3079): `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*, […]´.

important because it is a necessary condition to conclude that the differences `in their degrees of refrangibility´ cause their corresponding spots to fall in different locations on the wall behind the second prism (Netwon 1672, 3079). Newton´s argument is clarified in a letter to Lucas, in which he explains his reasoning concerning the second prism:

> […] in ye External causes you name there was no difference. The incidence of ye rays ye specific nature of ye Glass ye Prisma figure, &c were the same in both cases, & therefore could not cause ye difference: [it being absurd to attribute the variation of an effect to unvaried causes.][2] All things remained ye same in both cases but ye rays, & therefore there was nothing but ye difference of their Nature to cause ye difference of their refraction.
>
> (Turnbull 1960, 256f.)

This passage clearly shows that Newton´s conclusion that sunlight consists of rays with different refrangibilities, which are the cause of the length of the spectrum, is based on his reasoning regarding the second prism. This reasoning explains the different refractions behind the second prism that result in the different locations of the red and blue spots on the wall, which are caused by differences in the natures of red and blue rays.

Let us focus on this part of his reasoning as a simple and paradigmatic case of a Newtonian proof by experiment. It already contains all of the ingredients we need for our discussion. A short and simple reconstruction of Newton´s argument is as follows:

Experimental Data (*P*): In the absence of any differences in external influences, the refractions of rays stemming from different parts of the spectrum differ.

Theoretical Conclusion (*C*): These differences in refraction are caused by an internal (`non-external´) difference in the light rays.

In modern terms, this is a causal conclusion drawn from the premises of a difference test under conditions of homogeneity. Based on this reasoning, it is reasonable for Newton to insist that `the proper Method for inquiring after the properties of things is […] not by deducing it only from a confutation of contrary suppositions, but by deriving it from Experiments concluding positively & directly.´ (Turnbull 1959, 209f.). According to the above argument, experimental data determine a causal proposition of Newton´s theory.

The conclusion is not deductive, as Newton invokes the principle of causality in the sense that `any difference is caused by a difference´. In addition, the description of the experimental data leads to the articulation of a general statement and thus is characteristic of induction. Newton is well aware that his experimental proofs are based on `principles of physics´[3], and he repeatedly emphasizes that his method is not deductive[4]. For Newton, the

[2] The brackets are part of the quoted text and indicate that the text was added by Newton's own hand to a handwritten copy of his original letter (Turnbull 1960, 260, fn. 1 and fn. 3).
[3] Cf.:

principles of experimental physics are among the methods used for proof; they are not premises of a deduction. However, we might also reconstruct his proof in a deductive form using as premises particular statements and explicitly stated principles, such as the principles of causality, induction and the constancy of nature (Müller 2015a, 324ff.). Nevertheless, we need not be concerned with the details of such an explicit or even formal reconstruction. Likewise, we need not be concerned with causal reasoning or causality here. As we will see in the next section, the strength of Müller´s Goethean argument against Newton is that it shows that Newton´s proof is underdetermined *given Newton´s method of proof*. The salient point of Müller´s argument concerns not Newton´s particular method of experimental proof but rather its underlying *description* of the experimental data based on the concept of a ray.

2. Experimentum Lucis

Müller bases his argument for the underdetermination of Newton´s theory on the inversion of Newton´s experiments, as proposed by Goethe and later realized, independently and in different ways, by Holtsmark, Sällström, Nussbaumer, Grebe-Ellis and Rang. The inversion of the experimentum crucis is called the `experimentum lucis´ and has been presented to the public in several exhibitions in Berlin and on other occasions. One could interpret Figure 1 as a representation of the experimentum lucis by literally identifying the black rays with rays of darkness transmitted by a dark source and literally interpreting the white paper background as a homogeneous `rayless´ white background (analogous to Newton´s darkroom). Given this interpretation of the experimentum lucis in analogy to a Newtonian interpretation of the experimentum crucis, applying Newton´s method results in a proof of the heterogeneity of darkness. In fact, we can simply exchange the `ray´ interpretations in the description of

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> […] the absolute certainty of a Science cannot exceed the certainty of its Principles. Now the evidence by wch I asserted the Propositions of colours is in the next words expressed to be from Experiments & so but Physicall: Whence the Propositions themselves can be esteemed no more than Physicall Principles of Science.
>
> (Turnbull 1959, 187)

[4] Cf., e.g.:

> […] the Method of Analysis, ought ever to precede the Method of Composition. This Analysis consists in making Experiments […] and in drawing general Conclusions from them by Induction, and admitting of no Objections against the Conclusions, but such as are taken from Experiments, or other certain Truths. For Hypotheses are not to be regarded in experimental Philosophy. And although the arguing from Experiments […] by Induction be no Demonstration of general Conclusions; yet it is the best way of arguing which the Nature of Things admits of, […] By this way of Analysis we may proceed from […] Effects to their Causes, […].
>
> (Newton 1931, 404), Query 31

Cf. also Newton´s fourth regula in the third edition of *Principia* (Cohen and Westfall 1995, 118).

the experimental data (*P*) and the theoretical conclusion (*C*) to yield a similar experimental proof. Furthermore, just as Newton explains the phenomena of the experimentum lucis in terms of a complex superposition of rays stemming from white light, the inverted theory explains the phenomena of the experimentum crucis in terms of a complex superposition of rays of darkness. Müller describes in detail how this inversion can be generalized to all types of prismatic experiments and even provides an algorithm to convert explanations and experiments.

Thus, we have two alternative theories explaining the same experiments in different ways, with no empirical or intrinsic criterion for determining which is preferred. One might argue that the Newtonian theory is preferable because of the predominance of darkness in our universe, which makes it more plausible to conceptualize darkness as a homogeneous background. However, from a theoretical perspective, the predominance of darkness is contingent. One might object that it is possible to decide between the alternative theories by considering experiments other than prismatic ones. However, as Müller notes, the validity of such arguments is far from clear when the inversion of the experiments and their explanations are taken seriously (Müller 2015a, 287-301, 392-409). In the end, the validity depends on how far the symmetries in nature extend (Müller 2015b, 591). For the sake of argument, let us, in the following, restrict ourselves to considering weak underdetermination and accept that, with respect to fixed prismatic experiments, there is a similarly rational and empirically equivalent alternative to Newton´s theory based on the concept of darkness rays. The question we address is how to analyse *this* situation and what follows from it with respect to Newton´s claim of proof.

3. Compatible Alternatives

Müller´s rejection of Newton´s claim of proof is based on the presumption that an alternative theory asserting the heterogeneity of darkness is logically incompatible with Newton´s theory. Given this presumption, it indeed follows that Newton´s proof cannot be *correct*, for `the result of a correct proof does not tolerate incompatible alternatives´ (Müller 2015a, 329; my translation).[5] In presuming that underdetermination goes hand in hand with logically incompatible theories, Müller follows the canonical definition of underdetermination proposed by Quine (1975):

> […] under-determination says that for any one theory formulation there is another that is empirically equivalent to it but logically incompatible with it, and cannot be rendered logically equivalent to it by any reconstrual of predicates.
>
> (Quine 1975, 322)

[5] Cf. also: `Proofs must be unambiguous; they do not survive similar proofs of the contrary´ (Müller 2015, 225), my translation.

Prima facie, there are several candidates, all invoking the ray concept, for substantiating the logical incompatibility of Newton´s optics (*N*, for short) with its alternative $\overline{N}$. In regard to colours, the properties of homogeneity or heterogeneity are attributed to different colours in both theories. This applies to purple and green, for example.[6] `Purple is created by homogeneous rays´ (*Pu*) is false according to *N* and true according to $\overline{N}$ (Müller 2015a, 346). `Rays of moderate refrangibility create green´ (*Gr*) is true in *N* and false in $\overline{N}$ (Müller 2015b, 590).

However, as Müller is well aware, the theoretical terminus `ray´ is ambiguous in these propositions. In *N*, `ray´ means `ray of light´, whereas in $\overline{N}$, it means `ray of darkness´. Common to both concepts is the understanding that rays are the entities that induce vision or, for simplicity, the entities that create colour. However, these entities originate from lucid bodies in *N*, whereas they originate from dark bodies in $\overline{N}$. Newton essentially defines light rays as the smallest components of light in Definition 1 of his *Opticks*. In a letter to Lucas, he presents his definition of light immediately preceding his definition of light rays:[7]

> […] by Light I understand any Being or Power of a Being, (whether a Substance, or any Power, Action, or Quality of it) which *proceeding directly from a lucid Body* is adapted to excite Vision.
>
> (Turnbull 1959, 169; my emphasis)

This definition excludes rays of darkness as entities of *N*. However, the alternative theory $\overline{N}$ simply presumes an alternative definition obtained by replacing `lucid´ with `dark´ in Newton´s definition. The identity criteria for the underlying theoretical entities are not the same in the two theories. Thus, the underlying entities themselves also are not the same.

The truth or falsehood of each proposition (*Pu*) and (*Gr*) depends on the theory. This demonstrates that the term `ray´ refers to different entities in the two theories, or, similarly, that the terms `ray of light´ and `ray of darkness´ do not co-refer. This also follows from the fact that the words `lucid´ and `dark´ have the same meaning in both theories and do not co-refer. In addition to these words, the following words also have the same meaning in both theories: colour words in general; causal terminology, such as `cause´, `homogeneous´ and `heterogeneous´; and terminology referring to the equipment used in prismatic experiments, such as `prism´, `pinhole´ and `wall´. As Müller correctly notes in Müller (2015b), it follows that *N* and $\overline{N}$ are indeed two alternative theories because, in contrast to the theory-independent terminology, the two terms `ray of light´ and `ray of darkness´ are not

[6] The abbreviations `(Pu)' and `(Gr)', introduced in the following two sentences, indicate the colours purple and green.
[7] Newton´s definition of light rays in his *Opticks* stems from this letter.

interchangeable. Thus, for *N* and $\overline{N}$, there is `no way of systematically converting one into the other by reinterpretation sentence by sentence´ (Quine 1992, 97), thereby rendering those theories logically equivalent.

However, because the concepts of a ray as invoked in *N* and $\overline{N}$ do not co-refer, it also follows that the two theories are not logically incompatible. This result is clear from the fact that propositions such as (*P*), (*Pu*) and (*Gr*) do not refer to the same entities in both theories. Instead, we have two compatible theories that include theoretical terms, namely, `ray of light´ and `ray of darkness´ that are irreducible to each other. *N* does not imply the negation of the heterogeneity of darkness because it does not contain the concept of darkness rays. Due to the definitions in both theories, terms in *N* cannot have meaning within the alternative theory $\overline{N}$ without $\overline{N}$ violating the criterion of simplicity and vice versa. Note that there is no problem with maintaining and understanding statements of both theories within ordinary language. However, in the context of theories, statements must satisfy a criterion of simplicity that calls for a minimum number of presumed entities.

In contrast to his point of view in Quine (1975), Quine later follows a suggestion from Davidson and reduces the underdetermination of theories to the existence of logically compatible theories containing irreducible theoretical terms. In Quine (1992, 97f), he distinguishes three cases. The first is `unproblematic´ and does not give rise to underdetermined theories. The second case is considered the basic one:

> *Case 2:* Again the other theory is logically compatible with ours, but […], it hinges on some theoretical terms not reducible to ours.

Case 3 is concerned with logically incompatible theories:

> *Case 3:* The two theories are logically incompatible. Donald Davidson showed me that this case can be reduced to Case 2 by the following maneuver. Take any sentence *S* that the one theory implies and the other denies. Since the theories are empirically equivalent, *S* must hinge on some theoretical term that is not firmly pinned down to observable criteria. We may then exploit its empirical slack by treating that term as two terms, distinctively spelled in the two theories. *S* thus gives way to two mutually independent sentences *S* and *S´*. Continuing thus, we make the two theories logically compatible.
>
> (Quine 1992, 97f.)

In fact, Müller´s case study is a prominent example that illustrates the manoeuvre that Quine merely describes in general. *N* and $\overline{N}$ are literally logically incompatible as long as the theoretical term `ray´ is used without specification in both theories.

However, sentences such as (*P*), (*Pu*) and (*Gr*) result in logically independent sentences as soon as \`ray´ is specified as \`ray of light´ in *N* and \`ray of darkness´ in $\overline{N}$. As both theories are empirically equivalent with respect to prismatic experiments and, because of the symmetry of the experimental data, equivalent with respect to any intrinsic criterion, the two alternatives are indeed underdetermined based on those experiments.

Thus, the underdetermination of the theory stems from its language, or, more precisely, from the possibility of different identity criteria for the underlying entities. In a seemingly paradoxical way, one might say that *N* and $\overline{N}$ are underdetermined by the *experiments* because they are determined by the *experimental data*. However, this is not a paradox to the extent that the identity criteria for the experiments do not imply the descriptions of the experimental data that are relevant for the conclusions drawn from the corresponding experiments. Those data presume the language of a particular theory. It is only within a given theory that the design of an experiment becomes intelligible. The experimentum crucis is designed to produce light rays that strike the second prism at the same incidence; in the absence of the concept of a light ray, it is impossible to describe the experimental data that are relevant to the conclusion drawn from the experiment. *N* is not determined by the experiments for the simple reason that the experiments do not determine the theory´s language. The inversion of prismatic experiments reveals that these experiments do not determine the theoretical concept of a ray because they do not determine the source of the ray. The underdetermination of the theories *N* and $\overline{N}$ by these experiments is therefore related not to the method of proof used but to the language used to identify the relevant experimental data.

Thus, Müller´s case study illustrates not only Quine´s thesis of underdetermination but also Quine´s doctrine of ontological relativity. *N* and $\overline{N}$ differ in the presumed domains of their presumed theoretical entities in the realm of optics. *N* quantifies over rays of light, whereas $\overline{N}$ quantifies over rays of darkness. It is the underlying ontology by which the two theories extend beyond observations to give rise to alternative conceptions of the phenomena probed by prismatic experiments, without any reasonable criteria by which to decide between these alternatives.

4. Truth and Provability

According to Müller, the inversion of Newton´s experimentum crucis demonstrates that Newton´s experimental proof is underdetermined. On this basis, Müller concludes that Newton´s experimentum crucis does not prove the heterogeneity of light. Consequently, Müller calls the heterogeneity of light a hypothesis (Müller 2016, 328, 333). However, I argued in the previous section that *N* and $\overline{N}$ are not incompatible. The *correctness* of

Newton´s experimental proof is thus not called into question by inverting prismatic experiments.

Newton´s proof would not be underdetermined if one were to presume that rays of light exist but rays of darkness do not exist. Thus, Müller suggests adding this presumption to the proof as a premise (Müller 2015a, 225f.). He concedes that Newton´s proof would be conclusive under this assumption. In this case, the presumption of the existence of light rays and the non-existence of darkness rays would instead be an unproven hypothesis, and the heterogeneity of light would become a theorem proven based on the assumption of this hypothesis. In this respect, Newton´s proof is *incomplete* unless an unproven hypothesis is added as a premise.

However, this reasoning again does not account for the fact that the concept of a ray concerns the language of the theory rather than the content expressed within the theory. In *N*, the existence of light rays is not a hypothesis but follows from Newton's definition of light as any `Being or Power of a Being […] which proceeding directly from a lucid Body is adapted to excite Vision' (quoted above). Thus, the presumption of the existence of light rays is a postulate rather than a statement within the theory. A postulate defines the entities covered by a theory; a postulate concerns the domain of a theory, not what is said about the objects of that domain. Thus, a postulate is a statement that is not expressible within a theory because it concerns the possible values of the variables rather than which particular values satisfy certain predicates. By contrast, a hypothesis is a statement that is expressible within the language of a theory but is not provable within the theory. With respect to expressibility, theorems and hypotheses are on the same level; the only difference between them lies in their provability. In *N*, the statement that light rays have different properties that cause differences in refraction is a theorem and not a hypothesis. However, Newton is very explicit in the *Opticks* that any specification of the nature of those properties is not a theorem but a hypothesis in his theory. Whether light consists of particles is considered among the Queries in Newton´s *Opticks*, not among the proofs by experiment. Whether rays of darkness exist is not even a query within *N*. Such a question is not expressible within *N* because `rays of darkness´ is undefined within the language of *N*.

Consequently, it is impossible to complete Newton´s proof using any premise within the theory concerning the existence or non-existence of rays of light or rays of darkness. Furthermore, the completion of this proof is not necessary: given Newton´s method of proof and his description of the experimental data (*P*), the conclusion (*C*) indeed follows. The underdetermination of his proof is related to neither the *correctness of the drawn conclusion* nor the *completeness of the presumed assumptions*. Instead, it is related to the description of the presumed experimental data. This affects neither the correctness nor the completeness of the proof. Consequently, it does not affect the provability of the theory. It only demonstrates that the provability of the theoretical claims drawn from the experiments is a theory-dependent concept because it presumes the language of a particular theory.

Regarding truth, Quine does not even consider that the falsity of a theory follows from its underdetermination. Instead, he distinguishes two attitudes concerning two empirically equivalent, similarly rational and logically compatible theories involving irreducible theoretical terms: the *sectarian* attitude and the *ecumenical* one (Quine 1992, 99ff.). Whereas the latter regards both alternatives as true, the former concludes from the truth of one theory that the alternative is meaningless. In the end, Quine endorses the sectarian attitude because he does not see a reasonable way to state both alternatives within one inclusive language of a theory. His preference is a consequence of Quine´s immanent conception of truth based on his insight that `we have no higher access to truth than our evolving theory´ (Quine 1992, 99). Müller invokes Quine´s thesis of underdetermination and wishes to argue for it by providing a case study. However, from a Quinean point of view, the provability of a theory should not fall short of Quine´s insight that truth is a theory-dependent concept. From Quine´s logical perspective, any well-defined concept of truth is based on a Tarskian definition of `truth under a certain interpretation´, and any well-defined concept of proof depends on a particular theory and its interpretation. This leaves no room for a theory-independent conception of truth and provability. Consequently, underdetermination does no harm to claims of provability.

Newton´s reaction to his contemporary opponents is itself a good example of Quine´s sectarian attitude. As noted by Müller, the Jesuit Lucas presented inverted experiments to argue against Newton´s claims of proof (Müller 2016, fn. 15, 330). Newton is well aware of Lucas´s presumption of darkness rays in his inverted experiments (`light of ye black circle´ (Turnbull 1960, 257)). However, he rejects Lucas´s critique by insisting that such rays do not exist. Instead, he explains the phenomena observed in the inverted experiments in terms of the superposition of rays of light originating from a lucid body. According to Müller, Newton is blind to Lucas´s arguments and reacts rather dogmatically (Müller 2015a, 168). However, from a sectarian perspective, one should instead argue that Newton is well aware that proofs on the basis of $\overline{N}$ simply do not affect claims of proof within N. Newton consequently applies his terminology to explain his *and* the inverted experiments. Lucas, by contrast, applies the terminology of N to explain the Newtonian experiments, whereas he applies the terminology of $\overline{N}$ to explain the inverted experiments. This clearly violates the rules of experimental proof and is compatible with neither N nor $\overline{N}$ because, by multiplying the number of postulated entities, it contradicts the criterion of simplicity.

Of course, there is no need to prefer N to $\overline{N}$ unless the experimental data indicate some pertinent difference. However, to state the propositions of experimental proofs, one must adopt a specific theory. The only reasonable alternative is to abstain from stating these propositions in favour of meta-statements. However, this also does not refute any claim of proof.

I do not claim that Newton was aware of the fact that an alternative theory of optics based on the concept of darkness rays was empirically equivalent to his theory. However, he clearly distinguished between definitions, propositions (theorems) and hypotheses (conjectures), and his presumption of light rays was part of his definitions. Furthermore, Newton insisted on having proven the heterogeneity of light, but he never claimed that his experimental proofs ruled out alternative explanations. Instead, he rejected the idea that he had proven his theorems by means of demonstrating that it could not be otherwise. In this respect, provability and underdetermination are not incompatible according to Newton's understanding of experimental proofs. Newton intended to prove a theorem within his theory and did not care about the possibility of alternative theories. From this perspective, it is not Goethe who is the forerunner of Quine's thesis of underdetermination, as Olaf Müller sees it (Müller 2016, p. 323f.). Instead, one might view Newton as a forerunner of Quine's sectarian attitude towards underdetermination.[8]

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[8] Thanks are due to the participants of the philosophy of science colloquium at the Humboldt University Berlin for discussing a previous version of this paper.

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