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THE CONCEPT OF CAUSATION IN NEWTON'S MECHANICAL AND OPTICAL WORK**

Abstract. In this essay the authors explore the nature of efficient causal explanation in Newton's *Principia* and *The Opticks*. It is argued that:

(1) In the dynamical explanations of the *Principia*, Newton treats the phenomena under study as cases of Hall's second kind of atypical causation. The underlying concept of causation is therefore a purely interventionist one.
(2) In the descriptions of his optical experiments, Newton treats the phenomena under study as cases of Hall's typical causation. The underlying concept of causation is therefore a mixed interventionist/mechanicist one.

Keywords: Newton, (efficient) causation, *Principia, The Opticks*

1. Introduction

In this essay we will focus on an important subset of Newtonian causes and causal explanation, thereby neglecting at the moment other aspects. Here we elucidate one of the most vexed notions of causation and causal explanation in Newton's *corpus*: namely what in the context of seventeenth-century

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natural philosophy was called efficient causation. *Efficient causations* was to become the dominant form of causation (see especially [Schliesser 2007a, 2007b]). One notices the Aristotelian flavour here. It should be kept in mind that Aristotelian terminology was still *en vogue* during the seventeenth century. One of the author's has argued that, although Newton radically reinterpreted the notion of efficient "cause", he formulated his views on natural philosophy on a more abstract level in Aristotelian terminology [Ducheyne, 2005a]. It turned out that Newton veiled his innovative new style of natural philosophy in Aristotelian terminology.

To illustrate some of the aspects that we neglect let us briefly give some samples of these. First of all Newton stuck to final causes: the motion of the celestial bodies acts according to the law of universal gravitation, but their regular position (the primary planets revolve in concentric circles around the sun, in the same direction and very nearly on the same plane) can only be explained by "the design and dominion of an intelligent and powerful being" [Newton, 1999, p. 941]. Newton subtly added that the fixed stars are "constructed according to a similar design and subject to the dominion of *One*" [*ibid.*]. He further noted that we can only know God by his properties, attributes and "by the wisest and best construction of things and their final causes" [*ibid.*, p. 942]. Secondly, one could read Newton *Principia* as providing also formal causes, namely to laws of motion which dictate the trajectories bodies can describe (*cf.* [Joy, 2006]). We shall not be addressing final and formal causes in this essay.

There is a "Janus-like ambiguity" to the central concepts in the *Principia*: force, attraction, and gravity [McMullin, 1990, p. 72]. They appear to be "purely mathematical" as well as causal. How can this ambiguity be explained? How are we to make sense of this tension inherent to Newton's work? The nature—even the presence—of causal explanation in the *Principia* (first edition: 1687) is far from clear. Some passages in the *Principia* tend to support a positivistic reading (i.e. the reading that Newton was only interested in identifying mere regularities of succession), while others point to the importance of causation for Newton.

Let us look at some passages of the first kind. In a comment to *Definition VIII* Newton warns his readers that he is not "considering the physical causes and sites of forces" ("*virium causas & sedes physicas*"):

> Moreover, I use interchangeable and indiscriminately words signifying attraction, impulse, or any sort of propensity toward a center, considering these forces not from a physical but only from a mathematical point of view. *Therefore let the reader beware of thinking that by words*

> *of this kind I am anywhere defining a species or mode of action of a physical cause or reason, or that I am attributing forces in a true and physical sense to centers* (which are mathematical points) if I happen to say that centers attract or that centers have forces.
>
> ([Newton, 1999, p. 408]; see also [*ibid.*, p. 588]; emphasis added)

In this passage Newton seems to dispense with an agent-causal interpretation of attraction, where one attributes real causal agency to for instance the centre of the Sun [McMullin, 2001, p. 297]. The attraction depends on the distance from and the mass of the Sun (as Newton's formula of universal gravitation states), so that the Sun must be in some way causally involved. However, the manner of this involvement is left unspecified. The claim that the Sun is the immediate agent-cause of the celestial motion was untenable for Newton since he explicitly rejected *actio at distans without the mediation of something* else which is not material. This is precisely the point Newton made in a letter to Richard Bentley (on 25^{th} February 1692/3):

> It is inconceivable, that inanimate brute Matter, should, *without the Mediation of something not material*, operate upon, and affect other matter without mutual Contact, as it must be, if Gravitation in the Sense of *Epicurus*, be essential and inherent in it.
>
> ([Janiak, 2005, p. 102]; emphasis added)

Note that Newton is rejecting Epicurean atomism, which states that brute matter can *without the mediation of an immaterial cause* affect one other. On the Epicurean account, gravity is an essential and inherent property of particles. In another letter to Richard Bentley, Newton stated clearly:

> You sometimes speak of gravity as essential and inherent to matter. Pray do not ascribe that notion to me; for the cause of gravity is what I pretend not to know, and therefore would take more time to consider of it. [Janiak, 2005, p. 100]

Bodies are passive and are moved by active principles, i.e. immaterial agents: "[f]or we meet very little Motion in the World, besides what is owing to these active Principles" [Newton, 1954, p. 399]. In line with his metaphysical and theological outlook, he saw his theory as providing room for non-mechanical forces in nature. He stated this explicitly: "all these regular motions [i.e. celestial motions] do not have their origin in mechanical causes, since comets go freely in very eccentric orbits and into all parts of the heavens" [Newton, 1999, p. 940]. If gravity was inherent to matter this would mean that it is independent on Newton's "God of Dominion".

Newton's caveat that he is not "considering the physical causes and sites of forces" is not a rejection of efficient causation in general. It is a rejection of the supposition that the centres of bodies (which are only used in order to abstract and idealize the shapes of physical bodies in order to get an exact mathematical treatment of them) are agent-causes, i. e. that they by themselves directly produce gravity. In the scholium to section 11 of Book I, Newton wrote that establishing the forces in nature proceeds in the following consecutive steps[1]:

(1) Mathematics requires an investigation of those quantities of forces and their proportions that follow from any conditions that may be supposed.
(2) Then, coming down to physics, these proportions must be compared with the phenomena, so that it may be found out which conditions (or laws)[2] of forces apply to each kind of attracting bodies.
(3) And then, finally, it will be possible to argue more securely concerning the physical species, physical causes and physical proportions of these forces. Let us see, therefore, what the forces are by which spherical bodies, consisting of particles that attract in the way already set forth, must act upon one another, and what sorts of motions results from such forces. ([Newton, *Principia*, pp. 588–589]; our numbering)

The actual world is not the subject of Book I as it lacks physical content. The propositions of Book I are part of an autonomous enterprise.[3] As such, Book I is written with the purpose to demonstrate what will be the case if certain physical conditions hold (neglecting at that moment the real conditions in the actual world). Put differently: it is an investigation of what follows from the laws of motion given some force functions (= step 1). Then "*coming down the physics*" one starts by looking at the mathematical properties of motion present in the natural world infers from them which force-law

[1]One of the author's has provided a detailed account of Newton's methodology [Ducheyne, 2005b].

[2]This is an insertion made by Cohen himself.

[3]Newton seemed to think that Book I was an autonomous enterprise. He commented on Books I and II, as follows:

> "In the preceding books I have presented principles of philosophy that are not, however, philosophical but strictly mathematical—that is, those on which the study of nature can be based. These principles are the laws and conditions of motions and of forces, which especially relate to philosophy. (...) It still remains for us to exhibit the system of the world from these same principles." ([Newton, 1999, p. 783]; see also p. 561)

these motions exhibit (*cf.* "*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*") (= step 2). Thus in other words: from the mathematical properties present in nature one infers the physical agents. Newton is arguing from effects (Kepler's laws, or Kepler's rules as they were called at the time) to causes (centripetal forces). This was precisely what Newton was doing in the first propositions of Book III [*ibid.*, p. 802]. He inferred that a centripetal force is a necessary and sufficient cause of Keplerian motion. Thus: when we observe Keplerian motion in the solar system, we can conclude that it is produced by centripetal force. Finally, this results in a more secure way to discuss the physical species, causes and proportions of these forces (= step 3). Qua physical species and causes Newton had established that gravity cannot by explained by postulating a vortex theory and that a non-material cause should be introduced (*cf.* [Janiak, 2007]). Qua proportions of the force of gravity Newton had established that it acts according to an inverse-square centripetal force.

Let us also look at the second type of passages, where Newton explicitly stresses the importance of causal explanation. At the beginning of the *Principia* Newton declares:

> For the basic problem of philosophy seems to be to discover the forces of nature from the phenomena of motions and then to demonstrate the other phenomena from these forces. [Newton, 1999, p. 382][4]

In the *scholium* to the *Definitions*, Newton writes:

> But in what follows, a fuller explanation will be given of how to determine true motions from their causes, effects, and apparent differences, and conversely, of how to determine from motions, whether true or apparent, their causes and effects. [*ibid.*, p. 415][5]

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[4] The part continues:

> 'It is to these ends that Books 1 and 2 are directed, while in book 3 our explanation [*explicationem Systematis mundane*] of the system of the world illustrates these propositions. For in book 3, by means of propositions demonstrated mathematically in books 1 and 2, we derive from celestial phenomena the gravitational forces by which bodies tend toward the Sun and toward the individual planets. Then the motions of the planets, the comets, the moon, and the sea are deduced from these forces by propositions that are also mathematical.' [Newton, 1999, p. 382]

[5] In the case of the motion of the moon, Newton declares as follows: 'I wished to show by these computations of the lunar motions that the lunar motions can be computed from

In an unpublished draft intended for the *Scholium Generale* (second edition: 1713), Newton writes as follows:

> First, the phenomena should be observed, then their proximate causes — and afterward the causes of the causes—should be investigated, and finally it will be possible to come down from the causes of the causes (established by phenomena) to their effects, by arguing a priori. [Newton, 1999, p. 53]

In *The Opticks* (first edition: 1704) he writes 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]. In *Query 31* he writes:

> As in Mathematics, so in Natural Philosophy, the Investigation of difficult Things by the method of Analysis, ought never to precede the Method of Composition. This Analysis consists in making Experiments and Observations, 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. (. . .) By this way of Analysis we may proceed from Compounds to Ingredients, and from Motions to the Forces producing them; and in general, *from Effects to their Causes*, and from particulars Causes to more general ones, till the Argument end in the most general. This is the Method of Synthesis: And the method of Synthesis consists in *assuming the Causes discover'd and establich'd as Principles, and by them explaining the phaenomena proceeding from them*, and proving the Explanations. ([*ibid.*, pp. 404–405]; our emphasis)[6]

The passages of the second type make a positivistic reading very implausible.[7]

their causes by the theory of gravity.' [*ibid.*, p. 869]. In Proposition 24, Book III Newton declares: 'Hitherto I have given the causes of the motions of the moon and seas.' [*ibid.*, p. 839].

[6] In the preface to the second edition (1713) Roger Cotes writes:

> 'Therefore they [natural philosophers] proceed in a twofold method, analytic and synthetic. From certain selected phenomena they deduce by analysis the forces of nature and the simpler laws of those forces, from which they then give constitution of the rest of the phenomena by synthesis. This is that incomparable best way of philosophizing which our most celebrated author thought should be justly embraced in preference to all others.' [*ibid.*, p. 386].

[7] For a defence of Newton as a causal realist see [Ducheyne, 2005].

How can this ambiguity be explained? The only plausible explanation seems to be that Newton was aware that he was telling an unconventional causal story.[8]

Let us now state the aims of this paper. Our first aim is to specify the sense in which Newton's story in the *Principia* was unconventional. The second aim is to clarify the similarities and the differences between that concept and the concept of causation underlying his optical work.

The structure of the paper is as follows. In Section 2 we briefly discuss the current debate between interventionism and mechanicism in the philosophy of causation. In Section 3, we give a brief summary of Ned Hall's causal dualism and his arguments for it, as developed in Hall (2004). These sections provide the instruments we will use in our analysis of Newton. In Section 4, which will be short, we show that these two "instruments" are useful for formulating interesting hypotheses about (i) what makes Newton's concept of causation in his mechanical work atypical and (ii) about the differences with causation in his optical work. In Section 5 and 6 we give our arguments in favour of these hypotheses.

2. Interventionism and Mechanicism

Despite the deep problems they face (for an excellent diagnosis, see Psillos, 2004), the two currently most prominent and elaborated accounts of causation, viz. *counterfactual interventionism and the mechanistic approach*, tend to be imperialistic (in the sense that they tend to regard alternative theories as rivals, rather than as complementary approaches). According to James Woodward's proposal, a relation between two variables X and Y is causal, if an intervention was made on X, the relationship between X and Y remained invariant, and the value of Y changed accordingly. An intervention is then defined as follows:

I1. I causes X.

I2. I acts as a switch for all other variables that cause X. That is, certain values of I are such that when I attains those values, X ceases to depend on the values of other variables that cause X and instead depends only on the value taken by I.

[8] This is also the explanation of [McMullin, 2001] (see pp. 296–299). We do not use McMullin's notion of dynamic explanations here, but take over the idea that Newton felt that he was dealing with a special type of causation.

I3. Any directed path from I to Y goes through X. That is, I does not directly cause Y and is not a cause of any causes of Y that are distinct from X except, of course, for those causes of Y, if any, that are built into the I-X-Y connection itself; that is except for (a) any causes of Y that are effects of X (i.e., variables that are causally between X and Y) and (b) any causes of Y that are between I and Y and have no effect on Y independently of X.

I4. I is (statistically) independent of any variable Z that causes Y and that is on a directed path that does not go through X. [Woodward, 2003, p. 98]

The intuitive idea is that I is an intervention variable for X with respect to Y, when all changes that occur in the value Y are produced only by changes in the value of X (which are directly brought about by I). I.1 states that the changes in X are produced by the intervention I. I.2 tells us that for some values of I, the value of X depends only on the value of I. In this way, we are able to rule out all other causes of X. I.3 informs us that I cannot directly cause Y and that I cannot be the cause of another variable (Z) that causes Y. Finally, I.4 says that there are no other variables, other than I, which produce Y.

In order to accommodate causally true statements such as "Changes in the position of the moon with respect to the earth cause changes in the motion of the tides", Woodward notes that interventions need not to be physically realizable, "an intervention (...) will be 'possible' as long as it is *logically or conceptually possible for a process meeting the conditions for an intervention*" ([*ibid.*, p. 132]; emphasis added).[9] Woodward's proposal is in his own words "monocriterial" [*ibid.*, p. 93] and in Woodward (2002) he argues that the relevant features of mechanisms "can be captured by the truth of certain counterfactuals" [*ibid.*, abstract, p. S366]. The idea is that the functional parts constituting a mechanism exhibit behaviour which conforms to generalizations that are invariant under interventions.

Similarly, mechanicists have attempted to accommodate counterfactuals in their mechanicist theories of causation. Stuart S. Glennan, for instance, claims that "a key feature of mechanically explicable laws is that there is

[9]This claim is highly problematic. Stathis Psillos forcefully notes: "We now have a much more liberal criterion of meaningfulness at play, and *it is not clear*, to say the least, *which counterfactuals end up meaningless by applying it*." ([Psillos, 2004, p. 301]; emphasis added). Woodward needs to tell more about the truth-conditions of counterfactual conditionals.

an unproblematic way to understand the counterfactual which they sustain" [Glennan, 1996, p. 63].[10] The presence or absence of a mechanism then explains why certain counterfactuals hold. In a more recent paper, Glennan recasts his definition of mechanism as follows:

> (M) A mechanism for a behavior is a complex system that produces that behavior by the interaction of a number of parts, where the interactions between parts can be characterized by *direct, invariant, change-relating generalizations.*
>
> ([Glennan, 2002, p. S344]; emphasis added)

Note that Glennan is only trying to explicate causation in the life sciences. A "direct, invariant, change-relating generalization" explicitly refers to Woodward's counterfactual approach: "it describes a relationship between two or more variables in which an intervention that changes only one variable will bring about a change in another variable" [*ibid.*, p. S354]. This renders Glennan's proposal somewhat circular: on the one hand, he wants to claim that mechanisms explain the counterfactuals they sustain, but, on the other hand, he wants to claim that interventionist counterfactuals explain (the behaviour of) a mechanism (see [Psillos, 2004, p. 308]). Peter Machamer, Lindley Darden and Carl F. Craver's proposal (also restricted to the life sciences) does not fare any better. According to their definition, "Mechanisms are entities and activities organized such that they are productive of regular changes from start of set-up to finish or termination conditions." [Machamer, Darden, & Craver, 2000, p. 3]. As Psillos has forcefully argued, their proposal cannot do without counterfactuals [Psillos, 2004, p. 314]. Talk about "activities" and attempts to characterize the interactions within a system unavoidably lead to counterfactual talk.

While Psillos is not yet prepared to claim that the mechanistic and counterfactual approach defend two different concepts of causation, he admits that "it is plausible to argue that there are these two broad strands in our thinking about causation" [Psillos, 2004, p. 289]. Rather, in line with his criticism on counterfactual interventionism and mechanicism, he argues:

> There is an asymmetry between the two accounts we have been discussing: mechanisms need counterfactuals; but counterfactuals do not need mechanisms. In other words, mechanistic causation requires counterfactual dependence but not conversely. It is in this sense, that the counterfactual approach is more basic than the mechanistic. (. . .) The

[10] Glennan emphasises that his mechanical theory of causation cannot explain causation in fundamental physics [Glennan, 1996, p. 50].

> causal effect can be found out, at least in favourable circumstances, *without* understanding the causal mechanism, if any, involved; but the causal mechanisms, even if they are present, cannot be understood without the notion of causal effect, that is without some notion of (counterfactual) dependence. [Psillos, 2004, pp. 315–316]

Ultimately, both strands provide understanding [*ibid.*, p. 317].

3. Ned Hall's Plea for Causal Dualism

Ned Hall has recently gone further and argued that causation, "understood as a relation between events", comes in at least two basic and fundamental different varieties:

> Events can stand in one kind of causal relation — *dependence* — for the explication of which the counterfactual analysis is perfectly suited [namely, had c not occurred, e would not have occurred] (…). And they can stand in an entirely different kind of causal relation — *production* — which requires an entirely different kind of causal analysis [namely, c produces e] (…).
> ([Hall, 2004, p. 226], *cf.* pp. 252–257; emphasis added)

If we put his view into a definition of causation, we get:

> C causes E, if and only if, [E counterfactually depends on C] or [there is a causal mechanism by which C produces E].

Hall argues that in some cases a reading in terms of production is required, in yet some others a reading in terms of dependence, and, in most cases, a reading in terms of both. Let us start with a quintessential example from Hall, which is intended to give an example of a case where only dependence is required:

> Suzy and Billy have grown up, just in time to get involved in World War III. Suzy is piloting a bomber on a mission to blow up an enemy target, and Billy is piloting a fighter as her lone escort. Along comes an enemy fighter plane, piloted by Enemy. Sharp-eyed Billy spots Enemy, zooms in, pulls the trigger, and Enemy's plane goes down in flames. Suzy's mission is undisturbed, and the bombing takes place as planned. If Billy hadn't pulled the trigger, Enemy would have eluded him and shot down Suzy, and the bombing would not have happened.
> [Hall, 2004, p. 241]

Billy's pulling the trigger *did not produce* the bombing, rather it neutralized a state-of-affairs that would have prevented the effect from occurring. The occurrence of the bombing *was dependent* on Bill's pulling the trigger, but not produced by it. In this example, the effect counterfactually depends on the cause, but there is no mechanism linking cause and effect. Counterfactual dependence "seems to be the only appropriate causal relation for such "negative events" to stand in" [*ibid.*, p. 256]. Hall counters the obvious counter-response that would read this example in mechanistic terms, as follows:

> A remarkably frequent but entirely unsatisfactory response is the following: Billy's action *is* connected to the bombing via a spatiotemporally continuous causal chain—it's just that this chain consists, in part, of *omissions* (namely, the various failures of Enemy to do what he would have done, had Billy not fired). (...) For there is no reason to believe that the region of spacetime these omissions occupy intersects the region of spacetime that Suzy and her bomber *actually* occupy; to hold otherwise is just to mistake *this* region with the region she *would have* occupied, had Billy not fired. [*ibid.*, p. 243]

In other cases there is a causal mechanism but no counterfactual dependence (because there is simultaneous over-determination). Suppose that Billy and Suzy are engaged in a competition to see who can shatter a target bottle first. Suppose further that Suzy throws her rock a split second before Billy. Suzy's throw is spatiotemporally connected to the shattering in the right way, but Billy's is not:

> Suzy's throw is a cause of the shattering, but Billy's is not. Indeed, every one of the events that constitute the trajectory of Suzy's rock on its way to the bottle is a cause of the shattering. But the shattering depends on none of these events, since had they not occurred the bottle would have scattered anyway, thanks to Billy's expert throw.
> [*ibid.*, p. 235, p. 253]

Counterfactual dependence is causation in one sense: it is sufficient for causation but not necessary.

An important aspect of Hall's view is that in typical cases of causation, both relations are present and production and dependence coincide [*ibid.*, p. 254, p. 265]. So though the relations are conceptually distinct, in the actual world their extensions overlap in most cases. Atypical cases of causation occur where there is a production relation without counterfactual dependence (e.g. overdetermination) or where there is a relation of counterfactual dependence without a production relation (e.g. double prevention).

4. Hypotheses about Newton's Concept of Causation

Referring to the material presented in Section 2 and 3, we can now formulate two hypotheses. The first is about Newton's mechanical work.

(H1) What makes the causal story of the *Principia* unconventional is that the phenomena under study *may be* cases of Hall's second kind of atypical causation.

In Hall's example of the second kind of atypical case, it is clear that there is no mechanism that links cause and effect. In the *Principia* Newton is dealing with cases where there is no known mechanism. We can assume this due to an epistemic limitation, or make the ontological claim that we are dealing with a special kind of causation (Hall's second atypical case). That is why we write "may be" in the hypothesis.

Our second hypothesis is about Newton's optical work:

(H2) In the descriptions of his optical experiments, Newton treats the phenomena under study as cases of Hall's typical causation. The underlying concept of causation is there is a mixed interventionist/mechanicist one.

In the remainder of this article, we give our arguments for these hypotheses.

5. Causation in Mechanics: Counterfactual Dependence without Production

5.1. Let us look back at Newton's explanation of the planetary motions. In Proposition 1, Book III (which concerns the circumjovial and circumsaturnian planets), Newton infers a centripetal force (tending towards Jupiter/ Saturn) from the observation that Kepler's second law holds (by Proposition 2 (or 3), Book I[11]); and from the observation that Kepler's third law holds he infers that this force varies inversely as the square of the distance (by Corollary 6 to Proposition 4, Book I).[12] In Proposition 2, Book III (which

[11] In propositions 1–3, Book I of the *Principia*, Newton demonstrates that if we see that a body describes areas proportional to the times (the effect), we may conclude that—given the laws of motion—this is produced by a centripetal force (the cause)—note that Newton does not take into account any resisting medium [*ibid.*, p. 403]. Given that the laws of motion are valid, Newton is able to deduce that the area law is caused by its necessary and sufficient causal condition: a centripetal force [Cohen, 1980, p. 63].

[12] For the secondary planets Newton's application of Corollary 6 is no surprise, since he assumes that the orbits of the circumjovial planets, e.g., do 'not differ sensibly from circles concentric with Jupiter' [*ibid.*, p. 797].

concerns the primary planets), he similarly infers a centripetal force (tending towards the Sun) from the observation that the second law holds (by Proposition 2, Book I) and that it varies inversely as the square of the distance from the observation that the third law holds for the primary planets (by (Corollary 6 to) Proposition 4, Book I[13]). The conditional sentences in Book I function as "inference-tickets"[14] for discovering forces. Moreover, in the case of the primary planets the inverse square law is proved "with the greatest exactness from the fact that the aphelia are at rest" since the slightest departure from an inverse square law would entail motion in the aphelia (by Book I, Proposition 45[15]) [Newton, 1999, p. 802].

Newton's inferences essentially follow from the law of inertia. Since the primary and secondary planets are not at rest nor move uniformly along a straight line, an impressed force (in this case, a centripetal force [*ibid.*, p. 405]) is acting on them [*ibid.*, p. 416]. For Newton "Force is the causal principle [causale principium] of motion and rest" [Hall & Hall, 1962, p. 148]. Newton was surely no positivist as he strongly believed that the force of gravity truly existed [Newton, 1999, p. 943]. He did not, however, like many of his contemporaries (such as Huygens or Leibniz) endorse the customary form of causal explanation, namely a mechanistic explanation [*ibid.*, p. 940]. From ca. 1684–85, Newton proved with several experiments with *pendula* that a mechanical, all-pervasive ether could not exist [Dobbs, 1991, p. 144].[16] Vortices could not account for the regular celestial motions as they would slow them down. The celestial motions are explained by an immaterial cause acting *in vacuo*. These insights surely provided Newton with understanding (and they were compatible with his religious and theological agenda). Newton's rejection of Cartesian vortex cosmology is found in Proposition 53 of Book II. There he showed that vortex theory predicts that motion at the aphelia is slower because of compressing and that mo-

[13]Newton presupposes a circular approximation here.

[14]The term is due to Arthur Prior. In general "inference-tickets" link motions to forces, forces to motions, and macro-physical to microphysical forces composing them [Smith, 2002, p. 143].

[15]This proposition concerns ellipses. It is therefore more suitable than Corollary 6 to Proposition 4, which supposes circular motion.

[16]When one assumes that the ether exists, one would expect a retardation of the motion of the *pendulum* proportionally to the mass [Dobbs, 1991, p. 136]. Such retardation did not occur. Newton however stuck for some time to the idea of an ether. In 1684–1685 he already supposed the existence of great voids in space, without abandoning the (non-mechanical) ether [*ibid.*, p. 139].

tions at the perihelia are faster because of decompression [Newton, 1999, pp. 788–790]. This is contrary to the celestial motions we observe. Instead of seeing the solar system filled with *vortices*, Newton saw it as a Boylian vacuum where the celestial bodies could move freely [Newton, 1999, p. 939]. This meant that *only* a non-mechanical *cause* could account for the celestial movements (see [Janiak, 2007]). Newton never came up with a satisfying causal explanation of the non-mechanical force of gravitation. Accordingly, Newton relied on a counterfactual intuition of causation, which did not require Newton to provide details on the further causes producing gravity: if no impressed force acted upon a body, Keplerian motion would not have occurred. Although the law of inertia by itself cannot be observed (for the law of inertia states that bodies uniformly moving in along a rectilinear path are not being impressed by an external force ($= \neg EF(b_x) \rightarrow UR(b_x)$), we can determine its implications for motion indirectly: as terrestrial and celestial bodies do not describe uniform rectilinear paths, they are acted upon by an impressed force) ($= \neg UR(b_x) \rightarrow EF(b_x)$). So Newton derives $EF(b_x)$ from $\neg EF(b_x) \rightarrow UR(b_x)$ and $\neg UR(b_x)$. In essence, we are comparing the non-uniform and non-rectilinear motions of bodies with the uniform rectilinear motions stated by the law of inertia. William Whewell understood this counterfactual aspect very well:

> *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]; second emphasis added)

According to the law of inertia, bodies on which no forces are acting are at rest or move uniformly along a straight line. Since the celestial phenomena do not exhibit such inertial movement, they are necessarily acted upon by an impressed force. Note that in order to back up causal claims in the counterfactual sense, we need some theoretical background that informs us what happens when the putative causal factor is absent. In the case of orbital motion, this information is provided by Newton's first law: if a centripetal does not act upon a body, then this body will remain at rest or conserve its rectilinear inertial motion. This shows that the presence or absence of the centripetal force has a noticeable empirical difference. Because a mechanical ether could not allow *quam proxime* Keplerian motion [Newton, 1999, pp. 789–790]; also [Smith, 2002], we can infer that only a non-mechanical, non-resisting cause can account for the motion of the celestial bodies. Newton took the statement that gravity exists and is explanatory sufficient to mean that he had proved gravity as a primary or proximate cause for the heavenly and terrestrial motions, but that he did not succeed in discovering a further secondary or remote cause for gravity. Nevertheless, an explanation referring exclusively to the primary cause (and neglecting the secondary mechanism—if any—causing it) was fully legitimate to his mind. In CUL Add. Ms 9597.2, Newton thought the consequences of not accepting such "partial" explanations through: this would imply—a view impossible for Newton to accept—that the only satisfactory explanations were "causally complete", i.e. that they fully explain all causal agents occurring in between the observed phenomena and the ultimate cause:

> Otherwise, altogether no phenomenon could rightly be explained by its cause, unless the cause of this cause and the cause of the prior cause were to be exposed and so successively [and] continuously until the primary cause is arrived at.[17]

In CUL Add. Ms 3965.9, Newton explicitly articulated his views on explanation by means of distinguishing between proximate and remote causes:

> He who investigates the laws and effects of electric forces with the same success and certainty will greatly promote philosophy [i.e., natural philosophy], even if perhaps he does not know the cause of these forces. First, the phenomena should be observed, then their proximate causes—and afterward the causes of the causes—should be investigated, and finally it will be possible to come down from the causes of the causes (established by phenomena) to their effects, by arguing a priori. Natural philosophy should be founded not on metaphysical opinions, but on its own principles and [end].[18]

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[17] Ducheyne's translation of:

> "Alias nullum om[n]ino phaenomenon <per causam suam> recte explicari posset nisi causa <hujus> causae, & causa ~~priori~~ causae prioris redderetur & sic deinceps usque donec ad causam primam deventum sit."
>
> [CUL Add. Ms. 9597.2.11: f. 3^{r}]

[18] Cohen's translation of:

> "Qui leges et effectus Virium electricarum pari successu et certitudine eruerit, philosophiam multum promovebit, etsi <forte> causam harum Virium ignoraverit. ~~Nam~~ Phaenomena <observanda> primo ~~<spectanda> consideranda~~ <sunt>, dein horum causae proximae, & postea causae causarum ~~eruenda~~ eru-

Natural philosophy should proceed from phenomena to proximate causes, then from proximate causes to remote causes, and then finally—*a priori*—from remote causes to proximate causes. It is especially in this manuscript material that Newton's hierarchical account of causal explanation is apparent. Newton's explanation of celestial movement involves counterfactual dependence, and more precisely nomological dependence.

5.2. Newton's explanations involve causation as nomological-counterfactual dependence, while prima facie there is no production relation. So they may be examples of the second of Hall's atypical kinds of causation. In the *Principia*, Newton did not provide any further structural properties that would further explain the gravitational properties of bodies. He was reluctant to attribute a further cause to gravity:

> Thus far I have explained the phenomena of the heavens and our sea by the force of gravity, but I have not yet assigned a cause to gravity. Indeed, this force arises from some cause that penetrates as far as the centers of the sun and the planets without any diminution of its power to act, and that acts not in proportion to the quantity of the surface of the particles on which it acts (as mechanical causes wont to do) but in proportion to the quantity of solid matter, and whose action is extended everywhere to immense distances, always decreasing as the squares of the distances. (...) *I have not yet been able to deduce from phenomena the reason for these properties of gravity*, and I do not feign hypotheses. ([Newton, 1999, p. 943]; emphasis added)

As we have seen earlier, in his comment to *Definition VIII* he warned his readers that he was not "anywhere defining a species or mode of action of a physical cause or reason". Newton surely was interested in a further explanation of gravity [Newton, 1979, cxxiii; Newton 1999, p. 943]. Newton pondered on different possibilities: divine intervention (see e.g., *De Gravitatione* [Hall & Hall, 1978]), kinds of non-mechanical ethers (for instance see *Query 28* of *The Opticks*), active principles and spirits (on these matters see: [Dobbs, 1991; Heimann, 1981; McMullin, 1978]) and an interaction-field, in which gravity is a single action or operation between two bodies

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enda; ac tandem a causis <supremis causarum> per phaenomena stabilitis, ad ~~<causas> caus phaenomena~~ <eorum effectus>, ~~<eorum causas proximas>~~ argumentando a priori, descendere licebit. ~~Et inter Phaenomena numerandae sunt actiones mentis quae nobis innotescunt quarum conseij sumus~~ Philosophia naturalis non in opinionibus Metaphysicis, sed in Principiis propijs fundanda est; & haec [end]" [CUL Add. Ms. 3965.9: f. 109^{v}]

[Stein, 2004, pp. 287–288]. None of them seemed to satisfy his rigid criteria of scientific demonstration. He left the further physical mode of action of gravity unspecified.

6. Causal Mechanisms and Interventionism in the Experiments on Prismatic Dispersion

6.1. Although we shall focus on Newton's argument that white light consists of rays differently refrangeable, this example is meant to be representative for Newton's optical work in general. We will focus here on Newton's first optical paper to the Royal Society, *New Theory about Light and Colors* (1672), which contains his first enunciation of his theory of light, and on the corresponding material from *The Opticks*.[19] For the reader's convenience, let us briefly describe two of the central experiments in Newton's paper. For the first experiment Newton darkened his chamber and made a small circular hole in the window-shuts to let in an amount of the sun's light. He then placed a prism at that hole. As a result, the light was refracted on the wall. When the sun's light hits the prism, all colours of the spectrum appear. Closer examination reveals that the image on the wall is not circular—as it should have been according to the received view of refraction[20]—but has an oblong form. If one assumes that all rays are equally refrangible, then in the position of minimal deviation[21] (where the angle of divergence at incidence and the angle of refraction are equal) the refracted image must be geometrically similar to the shape of the source. The second experiment is Newton's famous *experimentum crucis* [Westfall, 1980, pp. 213–214]; for Newton's description see [Cohen, 1958, pp. 50–51; Newton, 1979, pp. 46–48].[22]

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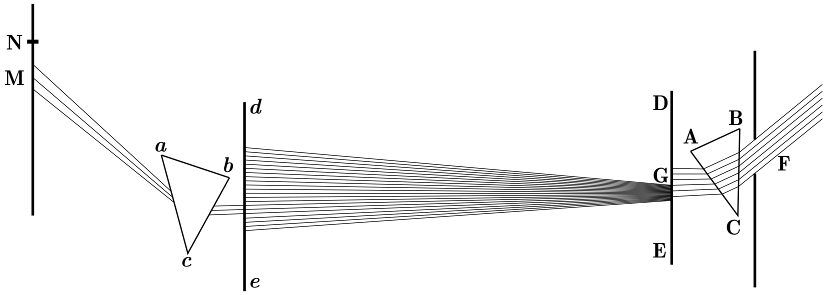
[19] Further differences between these two works are irrelevant for our present purposes.

[20] According to this view, we can expect an elongation, except for the position of minimal deviation. But the experiment Newton conducts precisely assumes this position [Sabra, 1967, p. 237].

[21] This position presupposed but not mentioned by Newton in his paper. It is mentioned in *The Opticks*, see [Newton, 1979, p. 28].

[22] The proto-version of this experiment can already be found in Newton's Trinity notebook (1666) [McGuire & Tamny, 1983, p. 468]. It should be stressed that this experiment is idealised. As Laymon has pointed out, Newton assumes that: (1) the light refracted by the second prism was described being of a single colour and that (2) that this light was or diffused or dilated [Laymon, 1978, p. 53, p. 56]. This will be the case if the ray has an equal breadth as the hole in the second board. The *experimentum crucis* refutes Hooke's theory on the assumption that an idealised description of the resultant image is used (it is precisely assumed here that the diameter of the hole is equal to the breadth of a



Newton took two boards and two prisms (see figure). He put the first board behind the prism at the window, so that the light might pass through a small hole. Then he installed the second board where again the light could pass a small hole and reach the prism placed behind the second board. This second prism was fixed; the first prism was slowly moved about its axis. As several colours passed through the second prism, their colour did not change and each colour was refracted at a specific angle. Newton observed that although the angles of incidence were the same, the angles of refraction were different.[23] The *experimentum crucis* showed that rays preserved their colour as well as their degrees of refrangibility upon being refracted through a second prism and that each colour had a specific degree of refrangibility. Newton also described the variations he pursued: he refracted homogeneous colours with prisms, reflected them with bodies, intercepted them with the coloured film of air interceding two compressed plates, transmitted them through coloured mediums, and through mediums irradiated with other sorts of rays [*ibid.*, p. 54].[24] It was never the case that a new colour was produced. After describing the outcome of the *experimentum crucis*, Newton wrote:

> And so the true cause of the length of that Image was detected to be no other, then that *Light consists of Rays differently refrangible* which, without any respect to a difference in their incidence, were according

single colour) and because, as it stood, Hooke's theory could not give a more quantitative description of the experiment [Laymon, 1978, pp. 69–70].

[23]Newton based his theory of colours almost exclusively on prismatic colours. The "mechanical philosophers" before him (e.g., Descartes) had dismissed the distinction between real and apparent, i.e. prismatic, colours [Schaffer, 1989, p. 74]. Newton's underlying premise is that radiant colours have a conceptual primacy over those of bodies [Shapiro, 1993, pp. 6–7].

[24]Newton's *ceteris paribus* clause was not entirely empty, as Worrall claims [Worrall, 2000, p. 57, footnote 7]. But evidently Newton does not take into account other variables like the temperature of the air or the glass, the atmospheric conditions, or other conditions.

> to their degrees of refrangibility, transmitted toward divers parts of the wall. [Cohen, 1978, p. 51]

> Colours are not *Qualifications of Light*, derived from Refractions, or Reflections of natural bodies (as 'tis generally believed,) but *Original and connate properties*, which in divers Rays divers. Some rays are disposed to exhibit a red colour and no other; some a yellow and no other, some a green and no other and so for the rest. [*ibid.*, p. 53]

Newton afterwards starts enumerating some more "instances of nature" that can be explained by his new theory of light (e.g. the colours of the rainbow, the phenomena of infusion of *Lignum Nephriticum*, leaf gold, fragments of coloured glass) [*ibid.*, pp. 55–6].[25] The fact that the refraction of the first prism was neutralised or re-refracted by the second prism, suggests that rays of light are refracted constantly. More precisely: rays emerging from the first prism at the greatest angle of refraction are equally re-refracted by the second prisms; similarly, rays emerging at the least angle of refraction are least re-refracted by the second prism. *Idem* for all intermediate rays of the spectrum. Thus, each part of the spectrum has its own inherent degree of refrangibility. This apparently entails that for each two different rays of light, when the first is refracted more than the second in one transparent medium, the first will always be refracted more in any other medium [Worrall, 2000, pp. 56–57]. White light consists of a heterogeneous mixture of different rays with an inherent degree of refrangeability. Newton could indeed understandingly[26] claim that to every colour there corresponds a specific degree of refrangibility, but not that white light is a heterogeneous aggregate.[27] What are the hidden assumptions used to arrive at the conclusion that lights *consists* of rays differently refrangible? Newton believed that

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[25] This seems to imply that Newton was thinking in terms of analysis-synthesis here: after that the true causes have been established, they can be applied to phenomena that were not included in the original analysis. Newton claimed that he proceeded in the first two books of *The Opticks* by analysis and that he had provided an instance of synthesis at the end of the first book [Newton, 1979, p. 405].

[26] The fact that Newton assumes that a single experiment can reveal the universal qualities of light, seems to stem from his belief in the uniformity of nature. Today we know that there are mediums in which red colours are more refracted than violet ones (e.g. dye fuchsine, iodine vapour), and that the refrangibility of a ray can be modified (e.g. in the Doppler effect where it is reflected from a moving mirror). See [Worrall, 2000].

[27] Hooke claimed that his pulse hypothesis could equally account for the experimental results without conceding the heterogeneity of white light [Sabra, 1967, pp. 233–234]. Hooke thought of the pulse of white light as the resultant of a large number of 'vibrations' each of which when differentiated would produce a given colour. Hooke's ideas were

his explanation was causally parsimonious. If we do not accept that light consist of rays differently refrangible than we have to suppose that a different causal mechanism occurred at the first prism than and the second one [Worrall, 2000, p. 59]. At the first prism the rays where created (creation), in the second the created rays were refracted (separation). If we suppose that light consists of ray differently refrangible the effects in both prisms can be explained. Colours are never created but only separated [Shapiro, 1993, p. 11].[28] This converges with what Newton writes in a comment on an experiment in *The Opticks*:

> 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, 1978, pp. 55–56]; emphasis added)[29]

We conclude that Newton provided a mechanism that explained the oblong form NM in minimal deviation: the structural heterogeneity of white light. To put it more precise: according to Newton, the *constitution* of white light as a heterogeneous mixture of different rays, which in their turn are disposed (see esp. [Cohen, 1978, p. 53]) to be refrangible at constant rates, is the cause of prismatic effects. Newton claimed that his optical theory had unravelled the constitution of white light but not the rays composing this mixture (*cf.* gravity as a proximate cause).[30]

later reintroduced in the nineteenth century: Gouy demonstrated that white light can be represented as the superposition of an infinite number of waves each corresponding to one of the spectrum colours. In both cases the prismatic colours are generated by the prism and hence the heterogeneity of white colour is absent in their explanation [*ibid.*, pp. 280–281].

[28] They can also be recombined [Cohen, 1978, pp. 58–59]. If a lens is placed after a prism, it will make the rays converge again at a certain (white point) point.

[29] Sabra notes: "the original compositeness of white light (whatever be the term, wave or otherwise, in which it is conceived) must have a definite *physical* meaning" [Sabra, 1967, pp. 278–279]. As we have seen in section 1, "the physical", according to Newton, is not identical to "what can be described by mechanical impact forces".

[30] We assume that a mechanism refers to the constitution or structure of a phenomenon and not necessarily to its material constitution.

6.2. There is also a counterfactual sense that underlies Newton's thought in his optical work. Newton describes the experimental manipulations he performed in detail, as well as their effects. The text is full of phrases of the form "I put a prism there", "It turned or moved that prism", "I illuminated this object" or "I put a board there and made holes in it at that place". Sometimes he uses the word "cause" to describe the causal relations (e.g. "by turning it slowly to and fro around its Axis, I caused the Image which fell upon the second Board to move up and down upon that board, (...) ([Newton, 1979, p. 45], *cf.* p. 50, p. 329)). Sometimes causative verbs like "make" are used (e.g., "By turning the Prism ABC slowly to and fro abut its Axis, this image will be made to move up and down the Board *de*, (...) [Newton, 1979, p. 46]).

As we have seen in Section 3, the law of inertia gives us the theoretical background against which we can judge whether the movements of planets counterfactually depend on the influence of the Sun. In order to see the counterfactual dependence in the optical experiments, we have to make Newton's theoretical background assumptions explicit. A first assumption is the law of rectilinear propagation of light. It is however clear that Newton assumes that light travels in straight lines and a reflecting or refracting surface is needed to change the direction of the ray. This is obvious from the way he defines refrangeability (definition II), reflexibility (definition III) and the relevant angles (angles of incidence, refraction and reflection, definitions IV and V). Let us look at definition II and III:

> *Refrangibility of the Rays of Light, is their Disposition to be refracted or turned out of their Ways in passing out of one transparent body or Medium into another.* [*ibid.*, p. 2]

> *Reflexibility of Rays, is their Disposition to be reflected or turned back into the same Medium from any other Medium upon whose Surface they fall.* [*ibid.*, p. 3]

These definitions presuppose that without the passage from one medium into another or without a surface upon which the ray fall, no refraction or reflection occurs (i.e., the ray of light continues to travel in a straight line). A second crucial assumption is that refraction and reflection do not occur spontaneously. Given these assumptions, the experimental manipulations that Newton describes (*cf.* the examples above) are necessary for the effects that occur.

7. In Conclusion

The most important conclusions are of course the hypotheses formulated in Section 4, for which we now have provided arguments. Combining the two hypotheses, we see that there is something that unites Newton's causal talk in all his optical and mechanical work: counterfactual dependence. When Newton talks about efficient causation in his optical and mechanical work, there is always a counterfactual dependence relation. And there is a clear difference between the optical and the mechanical work: only the optical work invokes mechanistic causation.

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