Phenomena in Newton's *Principia*

Kirsten Walsh, University of Otago

Abstract

Newton described his *Principia* as a work of 'experimental philosophy', where theories were deduced from phenomena. He introduced six 'phenomena': propositions describing patterns of motion, generalised from astronomical observations. However, these don't fit Newton's contemporaries' definitions of 'phenomenon'. Drawing on Bogen and Woodward's (1988) distinction between data, phenomena and theories, I argue that Newton's 'phenomena' were explanatory targets drawn from raw data. Viewed in this way, the phenomena of the *Principia* and the experiments from the *Opticks* were different routes to the same end: isolating explananda.

0 Introduction

Newton described his *Principia* as 'experimental philosophy': theories were deduced from phenomena, rather than speculations. For example, in the General Scholium, which concluded later editions of *Principia*, he wrote:

> In this experimental philosophy, propositions are deduced from phenomena and are made general by induction. The impenetrability, mobility, and impetus of bodies, and the laws of motion and the law of gravity have been found by this method (Newton, 1999: 943).

This passage refers to the six phenomena listed at the start of book 3 of *Principia*. These propositions described patterns of motion, generalised from observations of the planets, earth and moon. It has been noted by many commentators, however, that these do not seem to fit any standard definition of 'phenomenon'.[1] Some have argued that Newton's labelling was mistaken, while others have argued that Newton was using the label 'phenomenon' to avoid using the term 'hypothesis', which would mark his work as speculative, rather than experimental (Davies, 2009: 217).[2]

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[1] See for example, (Densmore, 1995), (Harper, 2011) and (Shapiro, 2004).

[2] See (Anstey, 2005) for the early modern distinction between experimental and speculative philosophy.

I argue that Newton's choice of label was appropriate, albeit unconventional. Firstly, drawing on Bogen and Woodward's (1988) distinction between data, phenomena and theories, I argue that Newton's phenomena performed a specific function: they isolated explanatory targets. Secondly, I draw some comparisons between Newton's *Opticks* and his *Principia*. In the *Opticks*, Newton isolated his explanatory targets by making observations under controlled, experimental conditions. In *Principia*, Newton isolated his explanatory targets mathematically: from astronomical data, he calculated the motions of bodies relative to an isolated system. Viewed in this way, the phenomena of the *Principia* and the experiments from the *Opticks* are different routes to the same end: specifying the explananda. I conclude that Newton was not in error, nor using experimentalist rhetoric simply for political reasons.[3] He was, however, bending the meaning of commonly used terms to his own needs.

1 The Phenomena of Principia

Principia book 3 contained six phenomena:[4]

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[3] Whether Newton's *Principia* should be considered a work of experimental philosophy by the standards of his contemporaries is beyond my scope here.

[4] The six phenomena of *Principia* originated as 'hypotheses' in the first edition. Of the nine hypotheses stated in the first edition, five of them were re-labelled 'phenomena' in the second edition, and Newton added one more (phenomenon 2).

Phenomenon 1	*The circumjovial planets, by radii drawn to the centre of Jupiter, describe areas proportional to the times, and their periodic times – the fixed stars being at rest – are as the 3/2 powers of their distances from that centre.*
Phenomenon 2	*The circumsaturnian planets, by radii drawn to the centre of Saturn, describe areas proportional to the times, and their periodic times – the fixed stars being at rest – are as the 3/2 powers of their distances from that centre.*
Phenomenon 3	*The orbits of the five primary planets – Mercury, Venus, Mars, Jupiter, and Saturn – encircle the sun.*
Phenomenon 4	*The periodic times of the five primary planets and of either the sun about the earth or the earth about the sun – the fixed stars being at rest – are as the 3/2 powers of their mean distances from the sun.*
Phenomenon 5	*The primary planets, by radii drawn to the earth, describe areas in no way proportional to the times but, by radii drawn to the sun, traverse areas proportional to the times.*
Phenomenon 6	*The moon, by a radius drawn to the centre of the earth, describes areas proportional to the times.*

Table 1 Phenomena from *Principia* (Newton, 1999: 797-801)

There are several things to notice about these phenomena. Firstly, they are distinct from *data*: they describe continuing patterns of motion, rather than particular observations or measurements. So, while the phenomena are detected and supported by astronomical observations, they are not observed or perceived *directly*.

Secondly, they are distinct (to put it somewhat anachronistically) from *noumena*: they describe the motions of bodies, but not the *causes* of those motions, nor the *substance* of bodies.

Thirdly, they describe *relative* motions of bodies: in each case, the orbit is described around a fixed point. For example, phenomenon 1 takes Jupiter as a stationary body for the purposes of the proposition. In phenomena 4 and 5, Jupiter is taken to be in motion around a stationary sun.

Fourthly, these phenomena do not prioritise the observer. Rather, each motion is described from the *ideal standpoint* of the centre of the relevant system: the satellites of Jupiter and Saturn are described from the standpoints of Jupiter and Saturn respectively, the primary planets are described from the standpoint of the sun, and the moon is described from the standpoint of the Earth. Furthermore, *because* Newton doesn't prioritise the observer, effects such as phases and retrograde motions of the planets are not phenomena but only *evidence* of phenomena.[5]

Newton's use of the label 'phenomena' is somewhat puzzling, because these do not fit any standard definition. Densmore has pointed out that:

> Despite what might be suggested by their title, these 'Phenomena' are not directly observed, but rather are conclusions based on observations… They invoke not just observations, but planetary theory in current use by the astronomers of his time (Densmore, 1995: 307).

Densmore identifies two problems with Newton's choice of label. Firstly, the phenomena are not directly observed. Secondly, the phenomena are informed by astronomical theory.

Let's see how the term 'phenomenon' was explicitly defined in the eighteenth century. Firstly, in the 1708 edition of his *Lexicon Technicum*, John Harris gave the following definition:

> Phænomenon, in Natural Philosophy, signifies any Appearance, Effect, or Operation of a Natural Body, which offers its self to the Consideration and Solution of an Enquirer into Nature (Harris, 1708).

In 1736, this definition was updated:

> Phænomenon [...] is in Physicks an extraordinary Appearance in the Heavens or on Earth; discovered by the observation of the Celestial Bodies, or by Physical Experiments the Cause of which is not obvious (Harris, 1736).

And in the 1771 edition of the *Encyclopædia Britannica*, Colin Macfarquhar and Andrew Bell said:

> Phænomenon, in philosophy, denotes any remarkable appearance, whether in the heavens or on earth; and whether discovered by observation or experiments (Macfarquhar & Bell, 1771).

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[5] Newton used the phases of the planets to support phenomenon 3 (Newton, 1999: 799), and the retrograde motions of the planets to support phenomenon 5 (Newton, 1999: 799).

These definitions emphasise *observed appearance*. We have seen that Newton's phenomena describe relative motions from an ideal standpoint. They are, then, effects, but not appearances. So they don't fit the above definitions in any straightforward way.[6]

This reveals an interesting methodological feature of Newton's phenomena. Traditionally, 'phenomenon' seems to have been synonymous with both 'appearance' and 'explanandum'. For example, the ancient Greeks were concerned to construct a system that explained and preserved the motions of the celestial bodies as they appeared to terrestrial observers (Duhem, 1969). 2000 years later, Galileo and Cardinal Bellarmine argued over whether a heliocentric or geocentric system provided a better fit and explanation of these appearances (Duhem, 1969). This suggests that, traditionally, philosophers did not distinguish between phenomena and data. For Newton, however, these come apart. The six phenomena of *Principia* describe the motions of celestial bodies, but not as they appear to terrestrial observers. In this sense, they are not appearances, but they do require an explanation.

Phenomena had an important role in Newton's methodology. Passages such as the one I opened with are littered throughout Newton's writings. Moreover, Newton's emphasis on the empirical basis of his natural philosophy is an important feature of his methodology. So it seems reasonable to expect that Newton was working with a distinct notion of 'phenomenon'. In fact, Newton considered including a list of definitions in book 3 of the *Principia*.[7] 'Phenomena' was going to be definition I[8]:

> Phenomena I call whatever can be perceived, either things external which become known through the five senses, or things internal which we contemplate in our minds by thinking. As fire is hot, water is wet, gold is heavy, the sun is luminous, I am and I think. All these are sensible things and

[6] In philosophy nowadays, the term 'phenomenon' has a variety of uses, such as: (a) A particular fact, occurrence, or change, which is perceived or observed, the cause or explanation of which is in question; (b) An immediate object of sensation or perception; and (c) An exceptional or unaccountable thing, fact or occurrence. These do not resemble Newton's usage.

[7] Among the draft manuscript material relating to the second edition of *Principia* (MS. Add. 3965), there are definitions of 'body', 'vacuum', 'force' and 'phenomena'.

[8] Editing marks on the manuscripts show that this was initially intended to be 'Definition III', but Newton frequently revised the ordering of the definitions before eventually abandoning them.

> can be called phenomena in a wide sense. Those things are properly called phenomena which can be seen but I take the word in a wider sense.[9]

This definition does not include, among its examples, the motions of the planets. In fact, the examples provided do not look like Newton's six phenomena at all. It is true that these examples are generalised, so they are not data. Moreover, they are observable, so they are not noumena. But they are not relativized or idealised in any important sense. Rather, they can be acquired fairly directly via sensory experience. In contrast, Newton's six phenomena are not the sorts of effects or occurrences that can *become known through the five senses* alone, nor are they things that *we contemplate in our minds by thinking*. Rather, they describe patterns of behaviour, isolated and relativized by reference to theory. So Newton's six phenomena stretch his own putative definition.

2 Bogen & Woodward on 'Phenomena'

As we have seen, Newton's use of 'phenomena' is unusual: they are not observational data in the sense meant by his contemporaries (or himself, in draft definitions). Was he then wrong or disingenuous? In this section I introduce Bogen and Woodward's (1988) account of scientific reasoning, which ultimately vindicates Newton's use of 'phenomena'.

Bogen and Woodward have argued for an account of science in which data, phenomena and theory provide three levels of scientific explanation (Bogen & Woodward, 1988: 305-306) (see figure 1 below).

[9] MS. Add. 3965, f.422v (my translation). In the interest of clarity, I have flouted convention by omitting Newton's editing marks.

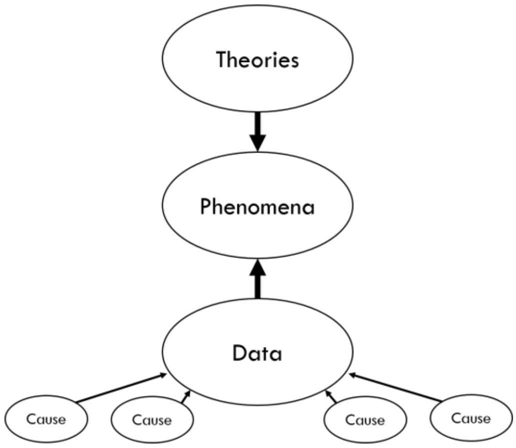

Figure 1 Bogen & Woodward's 3-tiered account of science

By the account, *data* are records produced by measurement and experiment that serve as evidence or features of phenomena. For example, bubble chamber photographs, discharge patterns in electronic particle detectors, and records of reaction times and error rates in psychological experiments. *Phenomena* are features of the world that in principle could recur under different contexts or conditions. For example, weak neutral currents, proton decay, and chunking and recency effects in human memory. *Theories* are explanations[10] of the phenomena.

Bogen and Woodward argue that explanatory theories provide systematic explanations of the phenomena, but don't explain the data. This is because data reflects causal influences beyond the explanatory target, while a phenomenon reflects a single, or small, manageable number of causal influences (Bogen & Woodward, 1988: 321-322). Consider the relationship between the Eddington experiment and General Relativity. In the Eddington experiment, a cluster of stars was photographed from a boat in the middle of the ocean, during a solar eclipse. These were then compared to photographs taken earlier under less turbulent conditions. The experiment captured the phenomenon of the displacement of starlight as it travels past the sun. General relativity explained the phenomenon, but did not explain the workings of the cameras, optical telescopes, and so on, that causally influenced the data.

[10] Bogen and Woodward take theories to be detailed systematic explanations, as opposed to singular-causal explanations (Bogen & Woodward, 1988: 322 n.17).

To summarise, on Bogen and Woodward's account, 'phenomenon' is defined *functionally* by its relationship to data and theory. Phenomena have the following features:

1. Distinct from data;
2. Inferred from data;
3. Describe isolated patterns; and
4. Explananda.

Bogen and Woodward do not consider Newton's work in their paper. However, in the next section, I show that we can characterise Newton's phenomena in such terms.

3 Turning observations into explananda

I now discuss the relationship between observations, phenomena and theorems in Newton's *Principia*, using phenomenon 1 as my case study. Firstly, I argue that Newton implicitly distinguished between observations and phenomena in a way that maps onto Bogen and Woodward's explicit distinction between data and phenomena. Secondly, I argue that Newton's phenomena perform the same supporting role for theorems as Bogen and Woodward's phenomena perform for theories.

Phenomenon 1 states that, with Jupiter at the centre, Jupiter's moons follow the area rule (see figure 2 below) and the harmonic rule (see figure 3 below) in relation to Jupiter. These patterns of motion are generalised from astronomical observation. Notice that phenomenon 1 treats Jupiter and its moons as an isolated system: Jupiter is a stationary body, and the motions of the moons of Jupiter are described in terms of their relationship to Jupiter.

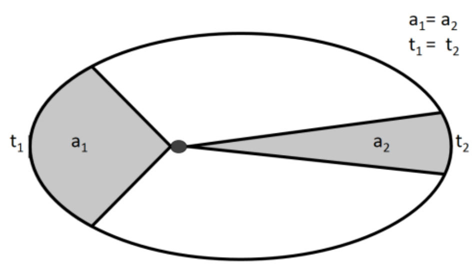

Figure 2 The Area Rule

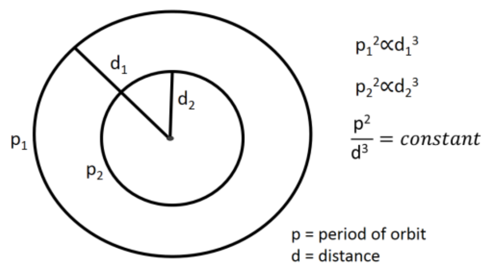

Figure 3 The Harmonic Rule

Consider how Newton obtained this phenomenon. To support the first part of this phenomenon, that Jupiter's moons describe areas proportional to their times around Jupiter, Newton said:

> This is established from astronomical observations. The orbits of these planets [i.e. the moons of Jupiter] do not differ sensibly from circles concentric with Jupiter, and their motions in these circles are found to be uniform (Newton, 1999).

In other words, the moons of Jupiter maintain constant distances from Jupiter. Moreover, they maintain a constant speed as they orbit Jupiter. So the moons of Jupiter maintain uniform circular motion, with Jupiter as the geometric centre. Therefore, they follow the area rule.

To support the second part of this phenomenon, that the periodic times of Jupiter's moons are as the 3/2 powers of their distances from Jupiter, Newton provided the following table:

Periodic times of the satellites of Jupiter				
	$1^d18^h27'34''$	$3^d13^h13'42''$	$7^d3^h42'36''$	$16^d16^h32'9''$
Distances of the satellites from the centre of Jupiter in semidiameters of Jupiter				
	1	2	3	4
From the observations of				
Borelli	$5^2/_3$	$8^2/_3$	14	$24^2/_3$
Towneley (by micrometer)	5.52	8.78	13.47	24.72
Cassini (by telescope)	5	8	13	23
Cassini (by eclips. satell.)	$5^2/_3$	9	$14^{23}/_{60}$	$25^3/_{10}$
From the periodic times	5.667	9.017	14.384	25.299

Table 2 Astronomical observations of the satellites of Jupiter (Newton, 1999: 797).

Newton took the periodic time of each of the four moons, in days, hours, minutes and seconds, and the distance of each moon from Jupiter, in semidiameters of Jupiter. The periodic times were from observations, as were the first four rows of distances. The final row of distances were calculated from the observed periodic times and the harmonic rule. This row illustrates the 'fit' between the expected distance (assuming the harmonic rule) and the observed distance.

These are not 'pure data'; their calculation involves extensive observational and theoretical work.[11] However, I argue they perform the role of data in Bogen and Woodward's sense. Firstly, as we have seen, they are the observational records from which the phenomena are drawn. Secondly, they contain more causal influences than the phenomena. Consider the latter point in more detail.

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[11] See (Densmore, 1995: 310-321).

In the *Principia* Newton indicated that the observations in table 2 above reflect a number of causal influences besides gravity. For instance, he explained how these calculations were obtained:

> Using the best micrometers, Mr. Pound has determined the elongations of the satellites of Jupiter and the diameter of Jupiter in the following way... (Newton, 1999: 797)

He went on to explain that the measurement of the diameter of Jupiter varied with the length of the telescope, because

> ...the light of Jupiter is somewhat dilated by its nonuniform refrangibility, and this dilation has a smaller ratio to the diameter of Jupiter in longer and more perfect telescopes than in shorter and less perfect ones (Newton, 1999: 798).

This illustrates Bogen and Woodward's notion that data shifts to phenomena. By attending to his theory about telescopes, Newton manipulated the data to control for distortion. So we can think of the observations as 'data' in a *methodological* sense: they are records from which phenomenal patterns can be drawn.

I now turn to the role of phenomenon 1 in *Principia.* Phenomenon 1 was employed (in conjunction with proposition 2 or 3, book 1, and corollary 6 to proposition 4, book 1) to support proposition 1, theorem 1, book 3:

> *The forces by which the circumjovial planets are continually drawn away from rectilinear motions and are maintained in their respective orbits are directed to the centre of Jupiter and are inversely as the squares of the distances of their places from that centre* (Newton, 1999: 802).

This proposition states that the motions of the moons of Jupiter are maintained by a centripetal force directed towards the centre of Jupiter, and this force decreases with the square of the distances of the moons from Jupiter.

This inference can be reconstructed as follows (see appendix for more detail):

P1. For all bodies x, if x exhibits a motion M, then M is caused by a force F. (established mathematically in book 1)

P2. Bodies $j_1, j_2, \ldots, j_n$ exhibit motion M. (phenomenon 1)

C. The motions of bodies $j_1, j_2, \ldots, j_n$ are caused by force F. (proposition 1 book 3)

P1 is stated in prose, but is a mathematical theorem. It is a conditional, stating the relationship between the motion of a body around a point and the direction and strength of the force that causes that motion. P2 describes the patterns of motion exhibited by the moons of Jupiter, but not the causes of that motion. Given that P2 satisfies the antecedent condition of P1, we can infer the consequent, C, from P1 and P2.[12]

Proposition 1 theorem 1 book 3 doesn't contain any information about the sizes or positions of Jupiter's moons, or the workings of telescopes. So, while it gives a causal explanation for the phenomenon, it gives no direct explanation of the observations. That is, given the number of causal influences on such observations, it would be impossible to predict the *apparent positions of the moons of Jupiter in the sky at a specific time* from proposition 1 alone. This is yet more evidence that, in the *Principia*, observations and phenomena are methodologically distinct. Moreover, this supports my reading of Newton's observations as data.

And so, Newton implicitly distinguished between observations, phenomena and theorems in a way that maps onto Bogen and Woodward's account. We saw this firstly in Newton's discussion of the observations, and secondly, in the role phenomenon 1 played in inferring proposition 1.[13]

4 Experiments in the *Opticks*

We have seen that the phenomena of the *Principia* provided the empirical evidence that licensed Newton's inference from mathematical to physical theorems. I shall now draw some comparisons between the *Principia* and Newton's other great work, the *Opticks*.

In the *Opticks* book 1, Newton employed a method of 'proof by experiments' to support his propositions. Each experiment was introduced to reveal a specific property of light. Using proposition 1 part I as my example, I shall explore this role for experiment.

Proposition 1 part I:

> *Lights which differ in Colour, differ also in Degrees of Refrangibility* (Newton, 1952: 20).

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[12] See (Fox, 1999, Harper, 1990, Stein, 1990) for discussions of deductive nomological argument in Newton's *Principia.*

[13] Phenomena 2-6 provided a similar kind of support for other propositions in book 3.

Newton provided two experiments to support this proposition. In experiment 1 Newton drew a line down the centre of a piece of black card, and painted one half red and the other half blue. Then he used sunlight to illuminate the card, and peered at the card through a prism, which he held close to his eyes (see figure 4 below). When he tilted the prism upwards, the card appeared to move upwards, the blue half (*dg*) appearing higher than the red half (*fe*). When he tilted the prism downwards, the card appeared to move downwards, the blue half (*δν*) appearing lower than the red half (φε). From this experiment, Newton concluded that the blue light refracts to a greater degree than the red light, and hence the blue light is more refrangible than the red light:

> Wherefore in both Cases the Light which comes from the blue half of the Paper through the Prism to the Eye, does in like Circumstances suffer a greater Refraction than the Light which comes from the red half, and by consequences is more refrangible (Newton, 1952: 21).

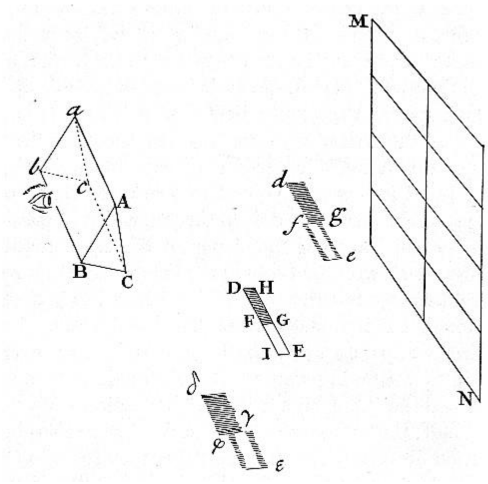

Figure 4 ***Opticks*, Book 1 part I, figure 11**

In experiment 2, Newton took the same piece of card and wound "a slender Thred of very black Silk" (Newton, 1952: 23) around it, so that several horizontal black lines passed across the colours. He stood the card upright against a wall, so that the colours stood vertically, side-by-side, and used a candle to illuminate it (since he performed this experiment at night). He placed a glass lens at a distance of six feet ("and one or two Inches" (Newton, 1952: 23)) from the card, and used it to project the light coming from the illuminated card onto a piece of white paper which was at the same distance from the lens on the other side (see figure 5 below). He moved the piece of white paper to and fro, taking precise note where and when the red and blue parts of the image were most distinct (the purpose of the black thread was to indicate distinctness: the image was most distinct when the lines created by the thread were sharpest). He found that when the red part of the image appeared most distinct, the blue part was faint and blurred; and when the blue part of the image was most distinct, the red part was faint and blurred. And that, in order to obtain a distinct red image, the paper had to be held 1.5 inches further away than it was to obtain a distinct blue image. He concluded:

> In like Incidences therefore of the blue and red upon the Lens, the blue was refracted more by the Lens than the red, so as to converge sooner by an Inch and a half, and therefore is more refrangible (Newton, 1952: 25).

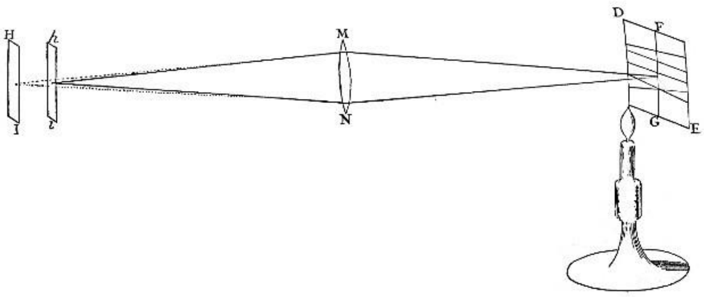

Figure 5 *Opticks*, Book 1 part I, figure 12

In the scholium that followed, Newton pointed out that the red and blue light in these experiments were not strictly homogeneous. Rather, both colours were, to some extent, heterogeneous mixtures of different colours. So it was not the case, when conducting these experiments, that *all* the blue light was more refrangible than *all* the red light. And yet, these experiments demonstrate a general effect:

> But these Rays, in proportion to the whole Light, are but few, and serve to diminish the Event of the Experiment, but are not able to destroy it (Newton, 1952: 26).

This highlights the fact that, here, Newton was describing *ideal* experiments in which the target system had been *perfectly isolated*.[14]

This discussion of Newton's phenomena reveals some continuity in Newton's methodology. The *point* of Newton's articulation of the phenomena in the *Principia* is the same as his observations and experiments in the *Opticks*. Both identify and isolate a pattern or regularity. In the *Opticks*, Newton isolated his explanatory targets by making observations under controlled, experimental conditions. In *Principia*, Newton isolated his

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[14] The examples I have just discussed are particularly clear cases of the 'proof by experiment'. There is variation amongst the experiments Newton introduces, but the general point holds.

explanatory targets mathematically: from astronomical data, he calculated the motions of bodies with respect to a central focus. Viewed in this way, Newton's phenomena and experiments are different ways of achieving the same thing: isolating explananda.

5 Conclusion

I have argued that Newton works with an implicit distinction between observation, phenomenon and theorem that maps onto Bogen and Woodward's explicit distinction between data, phenomena and theory. This, I take it, ought to be seen as grist for Bogen and Woodward's mill: they certainly do not attend to early modern examples in their discussion of their three-way picture of science. It may be that Newton's work is an early manifestation of the important distinction between 'data' and 'phenomena'.

My analysis has revealed several interesting features of Newton's methodology. Firstly, we saw that there is a continuity between Newton's *Principia* and his *Opticks*: Newton's phenomena and experiments are different ways of achieving the same thing: isolating explananda. Secondly, we saw that, while traditionally there was no real difference between phenomena and data, for Newton, these come apart.

Finally, Newton's use of 'phenomenon' fits, what I call, his 'rhetorical style'. Newton took the already familiar term and stretched it to fit his methodology. It is well known that Newton did this with many of his innovative philosophical ideas, such as 'force' and 'mass'. However, I argue that this is also a feature of many of Newton's methodological concepts: he 'borrowed' familiar terms and 'massaged' them to fit his own needs. Steffen Ducheyne has argued that Newton did this with his dual-methods of analysis and synthesis (Ducheyne, 2012: 5). Because Newton bends both terms and concepts to fit his needs, it is a mistake to focus too closely on definitions. We should instead understand his methodology in terms of the *roles* which concepts play. No one, not even Newton, explicitly stated that 'phenomena' were idealised explananda, isolated from much of the causal chaos that attends observations. Nonetheless, my analysis reveals that Newton used them as such. It seems therefore, that, when discussing Newton's methodology, we should emphasize divisions and functions over definitions.

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Appendix: Newton's inference to Proposition 1 Book 3

A longer reconstruction of this argument is as follows:

P1. If a body around a point obeys the area rule in relation to that point, then the motion of that body is maintained by a centripetal force directed toward that point. (Proposition 2 book 1)

P2. The moons of Jupiter around Jupiter obey the area rule in relation to Jupiter. (1st part of phenomenon 1 book 3)

C1. The motions of the circumjovial planets are maintained by a centripetal force directed toward Jupiter. (1st part of proposition 1 book 3 – from P1 & P2)

P3. If a body around a point follows the harmonic rule in relation to that point, then the centripetal force directed towards that point is inversely as the square of the distance from that point. (Corollary 6, proposition 4 book 1)

P4. The moons of Jupiter around Jupiter follow the harmonic rule in relation to Jupiter. (2nd part of phenomenon 1 book 3)

C2. For each moon of Jupiter, the centripetal force directed towards the centre of Jupiter is inversely as the square of the distance of that moon from the centre of Jupiter. (2nd part of proposition 1 book 3 – from P3 & P4)