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BACON'S IDEA AND NEWTON'S PRACTICE OF INDUCTION[1]

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Did not his Novum Organum give birth to the Art of Induction? [...] Has not Newton in his Opticks and in his Astronomy followed his precepts, step by step? (Berkeley quoted in Broadie, 2004: 41)

ABSTRACT

In this essay, I provide a Baconian reading of Newton's *Principia*. I argue that Newton scientific practice (especially in the *Principia*) was influenced by Bacon's methodised idea of induction. My focus will be on Newton's argument of universal gravitation.

1. Introduction

In this essay, I shall compare Francis Bacon's *idea* of the method of induction[2] with Isaac Newton's *practice* of induction. My focus will be on the *Principia*, since this is the *locus* where Newton explicitly proceeded from particulars to a universal conclusion. I shall argue – against popular agnosticism with respect to Bacon's influence on Newton – that Newton's argument for universal gravitation exhibits some features that are significantly similar to Bacon's ideas on the method of induction. One point should be clarified from the start. It should be clear

[1] The author is indebted to Erik Weber and Peter K. Machamer for their comments.

[2] For my present purposes: "induction" refers to ampliative reasoning processes in which we reason from particulars to a general conclusion.

from the outset that Bacon's method is intended as a *method of discovery* (*ars inveniendi*) (Malherbe, 1996: 75), which pertains to the Reichenbachian context of discovery. Newton's argument for universal gravitation, however, pertains to the *method of justification* – this pertains to the Reichenbachian context of justification. The context of discovery does not necessarily need to correspond to the context of justification.

Let us look at contemporary assessments of Newton's indebtedness to Bacon. In *The Cambridge Companion to Bacon*, Antonio Pérez-Ramos summarizes our current understanding of Bacon's influence on Newton, as follows:

> It is true that Newton does once refer to the "argument from induction" as a methodological principle, and that he dwells on the importance of the careful collection of particulars (i.e., Bacon's *historia naturalis*) and consecrates the use of the crucial experiment in the *Opticks*. Yet Newton never mentions Bacon by name, and philosophers and historians of science have been almost unanimous in rejecting this time-honored reading as wholly uncongenial, not to say inimical, to the mathematical tradition to which Newton obviously belonged. Nonetheless, Newton probably knew of the Baconian interpretation of his science and, as far as we know, did not voice any objection to it in his lifetime, though the full attribution to the Baconian inspiration was chiefly due to his posthumous editors Collin MacLaurin, Roger Cotes, and Henry Pemberton. (Pérez-Ramos, 1996: 319)

Bacon's influence is very modest, according to Pérez-Ramos: Newton knew Bacon's method of science, but it were mainly posthumous editors who were responsible for the Baconian spirit of Newton's work. I shall argue that, despite the fact that Newton never explicitly referred to Bacon and never explicitly cast his natural philosophy in overt Baconian terminology, Newton's scientific practice clearly exhibits some Baconian elements. I shall argue that in order to assess Bacon's influence on Newton, we should not restrict ourselves to the explicit utterances on these matters, but we should also look at Newton's scientific practice. What are these features, then? Bacon's influence lies in the *careful articulation of piecemeal generalization*. According to Bacon, we should never proceed from particulars to universals directly (i.e., simple enumerative induction), but do so by means of *partial generalizations* (which he called "medial axioms"). They are partial since they only refer to a limited set of elements or objects included in the final (universal) generalization. Subsequently, we try to further unify these partial generalizations in order to produce a truly "universal" generalization. Finally, we deduce and test the consequences of the resulting generalization, and adapt it correspondingly. All this is part of a careful and methodized procedure of induction. This process of piecemeal generalizing, which is a more careful pronunciation of scientific methodology than the Aristotelian ideal of deduction from "true and necessary" axioms, is the crux of Bacon's influence on Newton. It is exactly here that Bacon's idea of induction meets Newton's practice of it.

2. Bacon's Methodized Induction

In this section, I will look at the fundamentals of Francis Bacon's (1561-1626) method of induction.[3] My aim is not to scrutinize Bacon's method nor to criticize it, but simply to present the essentials of his notion of induction. As is widely known, Bacon rejected the Aristotelian methodology of syllogistic demonstration (Sargent, 2001: 313) and opted for a more complex procedure of ascending from particulars to universals in an "orderly method" (Bacon, 1676: 3, 22). This shift was crucial. According to Bacon, syllogistic demonstration confused words with the order of things and corrupted natural philosophy (ibid.: 2, 9). Unravelling nature is not a simple matter, but a real struggle. One had to provoke and even "torture" nature in order to do so (for Bacon's idea of *venatio* and *vexatio*, see Pesic, 1999 and Rossi, 1996). Bacon's idea of science was that of an active and operative science (see Pérez-Ramos, 1988; Pérez-Ramos, 1996). A knower, according to Bacon, is essentially a maker. True knowledge refers to knowledge which is made or can be made (reproduced, modelled, fabricated, …) (Pérez-Ramos, 1996: 110). In order to know a phenomenon, we should be able to (re)produce it (ibid.:

[3] I will use Bacon's *Novum Organum* as a guide here (Bacon, 1676). This work was the second and incomplete part of Bacon's equally incomplete master project the *Instauratio Magna* (1620).

115). Put more precisely: "The capacity of (re)producing Nature's 'effects' was perceived as the epistemological guarantee of man's knowledge of natural processes in the external world." (Pérez-Ramos, 1988: 59). Accordingly, Bacon reacted to the Aristotelian dichotomy between products of nature (*naturalia*) and human arts (*artificialia*), by showing that there is no ontological difference between the spontaneous workings of nature and the workings which are directed or manipulated by man's purposive action (ibid.: 109; Pérez-Ramos, 1996: 110-116). Nature always maintains the same *modus operandi.* Let us now turn to Bacon's method of induction.

Bacon's inductive method starts with sensible experience "immediately drawn from things, as they appear" (Malherbe, 1996: 85). These "data" are then generalized to low-level axioms by means of the tables of induction. There are three kinds of tables:

> (1) *The table of essence and presence*, which enumerates all situations in which the nature under consideration is present (*cf.* "all instances that agree in their Nature, though by different matters"; ibid.: 22).
> (2) The *table of deviation or absence of degrees*, which lists all situations which are as similar as possible to the first table, but where the nature under consideration is absent.[4]
> (3) The *table of counter-instances*, which suggests experiments in order to search possible counter-examples.

Once we have applied these tables, we potentially acquire some low-level axioms or "living axioms". From these axioms more general ones, i.e. the fundamental laws of nature, can be derived. As Bacon pointed out:

> We must not permit the Understanding to leap or fly from particulars to remote and general Axioms, such as the principles of

[4] In the famous example of the nature of hotness, Bacons wrote: "We must first speak of those things, which seem not to the feeling to be hot, and yet are so potentially afterwards: we shall then descend to mention such things as are actually, or at the feeling hot; and to examine their strengths and degrees of heat." (ibid.: 25).

> Arts and Things, or by their constant verity to prove or discuss medial Axioms. But then Men may hope well of Sciences, when by a true Scale, and continual not intermitted degrees, we ascend from particulars to lesser Axioms, then to the medial, for some are higher than others; and lastly to universals: for the lowest Axioms differ not so much from naked Experience, but the suppressive and more general which occur, are rational and abstracted, and have no solidity. The medial therefore are those true solid and lively Axioms, wherein men[′]s fortunes and estates are placed, and above those also are the more general, if not abstracted, but truly limited by these medial of middle Axioms. (ibid.: 14)

In this way we obtain “knowledge of the forms”. Bacon believed that “the most general axioms should form the end rather than the beginning of scientific inference” (Peltonen, 1996: 16). His method proceeds along a strict hierarchy of increasing generality. From the fundamental laws it is possible to derive further deductions and new experiments. In this process, the method of analysis by exclusion enters the scene (ibid.). This is the only way to guarantee that the discovered causes are the true “forms” in nature: we show that no other cause can explain the nature under investigation – here too we use tables of presence and absence.

The “living axioms” mediate between the data and the forms. Crucial in Bacon’s conception of scientific methodology is the view that we ought to proceed from particulars to universal generalisations by mediate axioms:

Particular Event → Mediate Axioms → Universal Generalisation

As we will now see, Newton’s practice (especially his argument for universal gravitation as spelled out in Book III of the *Principia*) agrees with this characterization.

3. Newton’s Argument for Universal Gravitation

In this part, I will analyse Newton’s practice of induction by focussing on the argument for universal gravitation. The argument for universal gravitation, where celestial and terrestrial bodies are unified, is not straightforward. In this process of unification, Newton used various inductive reasoning steps. Let us briefly look at how Newton established his famous unification (for a more elaborate account of unification in Newton's natural philosophy, see Ducheyne, 2005a).

First, Newton demonstrated that the circum-jovial planets, the circum-saturnian planets, the primary planets and the Moon are (1) drawn towards their respective centres by a centripetal force, and, that (2) this centripetal force varies inversely proportional to the square of the distance from those centres (Newton, 1999: 802-5). This respectively follows from the fact that (1') they describe areas proportional to the times and (2') that their periodic times are as 3/2 powers of their distances from their respective centre.[5] Newton inferred the causal agents that are responsible for these observed, mathematical regularities. These "deductions" are validated[6] by propositions Newton proved earlier in Book I:

> Proposition 2:
> Every body that moves in some curved line described in a plane and, by a radius drawn to a point, either unmoving or moving uniformly forward with a rectilinear motion, describes areas around that point proportional to the times, is urged by a centripetal force tending toward that same point. (ibid.: 446)
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> Corollary 6, Proposition 4:
> If the periodic times are as 3/2 powers of the radii, and therefore the velocities are inversely as the square roots of the radii, the

[5] The proof for the Moon is different. This concerns Newton's famous Moon test. In Proposition 4, Newton shows (1) that terrestrial gravity extends to the Moon and that it does so by an inverse square law, and (2) that it is the force of gravity which causes the Moon to circle about the Earth. Newton calculated the distance the Moon would fall if deprived from all forward motion in one minute. The result of that calculation is 15 1/12 Paris feet. If gravity diminishes by an inverse square law and the Earth's gravity extends to the Moon, then it follows that a heavy body on the Earth's surface should fall freely in one minute through 60 times 60 the above 15 1/12 Paris feet (the Moon is approximately positioned at 60 Earth-radii from the Earth's centre) (Cohen, 1999: 205). This indeed agrees with terrestrial experiments (*cf.* Huygens's experiments with pendula).

[6] For the details, see Ducheyne, 2005b.

> centripetal forces will be inversely as the squares of the radii; and conversely. (ibid.: 451)

A first level of unification is reached in Proposition 5. We know that the primary planets are drawn towards the sun by an inverse square force, that the Moon is drawn to the Earth by a similar force, and that the secondary planets are drawn to their primary planets by a similar force. Since these revolutions are phenomena of the same kind, they must – according to the second rule of philosophising[7] – "depend on causes of the same kind" (ibid.: 806). The elements of its domain obviously are: the primary planets, the secondary planets and the Moon.[8] I will represent this as follows:

(1) $(F \sim 1/r^2)$ for domain D_1 (D_1 = [*p* = primary planets, *s* = secondary planets, *m* = Moon])

The force-function operates from *p* towards the Sun, from *s* towards Jupiter and Saturn, and from *m* to the Earth. In Corollary 1 Newton applied the third law of motion. He established that the sun is drawn back by the primary planets, that the Earth is drawn back by the Moon, and that Jupiter and Saturn are drawn back by their satellites. (1) is reinterpreted as follows:

(2) $(F \sim 1/r^2)$ for domain D_2 (D_2 = [*p* = primary planets, *s* = secondary planets, *m* = Moon, *S* = sun])

The force-function operates from *p* towards *S* (and conversely), from *s* towards Jupiter and Saturn (and conversely), and from *m* to the Earth (and conversely). Corollary 2 to Proposition 5 states that the gravity towards every planet is inversely as the square of the distance (ibid.: 805). In Corollary 3 he further extended his claim: all planets are heavy

[7] Rule 2 goes as follows: "Therefore, the causes assigned to the natural effects of the same kind must be, so far as possible, the same." (Newton, 1999: 795).

[8] The domain refers to those bodies that are drawn towards a centre. Therefore, at this stage the Sun is not an element of the domain. I will also take over Newton's distinction between the secondary planets and the Moon.

toward one another. And hence, Jupiter and Saturn, when in conjunction, sensibly perturb each other's motion by attracting each other, the Sun perturbs the lunar motions, and the Sun and the Moon perturb the sea (ibid.: 806). (2) is reinterpreted as follows:

(3) $(F \sim 1/r^2)$ for domain D_2

The force-function operates from *p* towards *S* (and conversely), from *s* towards *p* (and conversely), from *m* to the Earth (and conversely), and from every *p* to every *p*. We see how Newton step-by-step generalized the inverse-square relation (the final relation will be derived in step 7). Next, he reinterpreted Galileo's law of free fall in the following way (ibid.: 806-7).[9] The falling of heavy bodies takes place in equal times. Newton used experiments with pendulums to show that different materials of exactly the same weight (gold, silver, lead, glass, sand, salt, wood, water, and wheat) swing back and forth with equal oscillations. Such experiments make it possible to discern the time-intervals made by each swing with high precision. The motive force of a falling body is its weight. This force is proportional to the acceleration and the mass of the body (by Newton's second law). Since the acceleration for bodies in free fall is constant, the weight of bodies in free fall is proportional to their mass. Newton generalizes the outcome of the experiments with pendulums to all terrestrial bodies. In this way Newton arrived at a different unification:

(4) $(W \sim m)$ for domain D_3 (D_3 = [t = terrestrial bodies])

Since "there is no doubt that the nature of gravity toward the planet is the same as toward the Earth", this also holds for the other planets (ibid.: 807). As he wrote:

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[9] Newton does not mention Galileo's name here: "Others have long since observed that the falling bodies of all heavy bodies toward the Earth (at least making an adjustment for the inequality of the retardation that arises from the very slight resistance of the air) takes place in equal times, and it is possible to discern that equality of the times, to a very high degree of accuracy, by using pendulums." (Newton, 1999: 806-7).

> Further, since the satellites of Jupiter revolve in times that are the 3/2 powers of their distances from the center of Jupiter, their accelerative gravities toward Jupiter will be inversely as the squares of the distances from the center of Jupiter[10], and, therefore, at equal distances from Jupiter, their accelerative gravities would come out equal. Accordingly, in equal times in falling from equal heights [toward Jupiter] they would describe equal spaces, just as happens with heavy bodies on this Earth of ours. (ibid.)

Here Newton extended the domain of (4). Consequently a new unification arises:

(5) (W ~ m) for domain D_4 (D_4 = [*t* = terrestrial bodies, *bp* = bodies in the neighbourhood of other primary planets])

The force-function operates from *t* to the Earth and more generally from *bp* to *p*. In Proposition 7, Newton claimed that gravity exists in all bodies universally and is proportional to the quantity of matter in each (ibid.: 810). This follows from the fact that all parts of any planet A are heavy toward any other planet B. Since the gravity of each part is to the gravity of the whole as the matter of that part to the matter of the whole, and, since to every action there is always an equal reaction, it follows that planet B will gravitate in turn to all the parts of planet A, and its gravity towards any part will be to its gravity towards the whole of the planet as the matter of that part to the matter of that whole (ibid.: 810-11). So we get:

(6) (W ~ m) for domain D_5 (D_5 = [*b* = all bodies universally])

Finally, he generalizes the inverse square law for all bodies universally (ibid.: 811). He first argued that the force of the whole is the resultant of the forces of the constituting parts. Next, he showed that the gravitation

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[10] In modern terminology this can be demonstrated as follows. Huygens published the result that a body travelling in a circle needs a force proportional to v^2/r to keep it in orbit: $F = k.v^2/r$. Since v equals $2.\pi.r/t$: $F = k.4.\pi^2.r^2/t^2.r$. Multiplied by r/r: $F = k.4.\pi^2.r^3/t^2.r^2$. Since r^3/t^2 is a constant according to Kepler's third law, we can obtain: $F = (\text{constant})/r^2$. See Newton, 1999: 451.

toward each individual part is inversely as the square of the distance, which follows directly from Proposition 74, Book I (ibid.: 593, 811). By composition – “*componendo*” – of forces, the sum of the attractions will come out in the same ratio. Hence, all parts gravitate toward each other and this force varies inversely as the square of the distance from their centres.

(7) $(F \sim 1/r^2)$ for domain D_5.

So what Newton did is basically this: he extended the proportionality of weight and mass valid for bodies in free fall to all bodies, and, subsequently, he extended the inverse square law for celestial bodies to all bodies universally. The final result is the law of universal gravitation. The extension from one domain to another is an essential feature of Newton’s unification in Book III.

So far for the analytic part of Newton’s argument. Newton described the analysis as follows. It 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. And although the arguing from Experiments and Observations by Induction be no Demonstration of general Conclusions; yet it is the best way of arguing which the Nature of Things admits of, and may be looked upon as so much the stronger, by how much the Induction is more general. And if no Exception occur from Phænomena, the Conclusion may be pronounced generally. But at any time afterwards any Exception shall occur from Experiments, it may then begin to be pronounced with such Exceptions as occur. 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 particular Causes to more general ones, till the Argument end in the most general. (Newton, 1979: 404)

We ought to proceed from effects to particular causes and then to general causes:

Effects → Particular Causes → General Causes

Newton typically proceeded from particulars (e.g., motion of a planet) to mediate axioms (e.g., Kepler's "laws"). Then these mediate axioms are investigated and used to arrive at the universal axiom: the law of universal gravitation. This law is realized through a careful step-by-step procedure of partially generalizing experimental results. But the story does not stop with the analytic phase. Next comes the moment of synthesis. The method of synthesis consist 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.: 405)

The synthesis starts after Proposition 8 and stretches out to the very end of Book III. Newton showed that the irregular motion of the Moon, the tides, the motion of comets can be deduced from the causes proposed by the theory of universal gravitation. The phase of synthesis concerns the testing of the generality of the general principles. If no problems occur, the principle can by stated as truly universal – which is the case in the *Principia*. Ultimately, the synthesis consists in testing the general principles obtained in the analysis.

Newton eliminated vortices as possible causes for the celestial motions. In other words, Newton applied the method of analysis by exclusion. Near the end of book II, Newton showed that the Cartesian hypotheses of vortices – the only alternative dynamical celestial theory at hand – faced some serious problems. In Section 9, Propositions 51-53, Newton showed that the vortices which carry the planets in their respective orbits cannot be self-sustaining and that their motion is inconsistent with Keplerian motion (Cohen, 1999: 187). Newton demonstrated that, if a solid sphere revolves with a uniform motion in a uniform and infinite fluid (under the further assumptions that the fluid is made to revolve by only the impulse of the sphere and that each part of the fluid perseveres uniformly in its motion), the periodic times of the parts of the fluid will be as the squares of the distances from the centre of the sphere (ibid.: 781). The periodic times are not as Kepler's harmonic law which tells us that they should be as 3/2 power of the distances (ibid.: 787). Moreover, the law of areas does not apply to them (ibid.:

789). According to the area law, a planet will move more slowly in the aphelion than in the perihelion. While according to “the laws of mechanics” the vortices ought to move more swiftly at the aphelion, since the space is narrower at the aphelion. In such vortex-system the periodic times will be as the squares of the distance and the law of area will not hold. Since we know that the periodic times are as 3/2 power of the distances and that the area law holds (very nearly), the *implicans* is rejected by *modus tollens*: a vortex-system does not cause the celestial motions.[11]

4. Conclusion

We have seen that Newton’s law of universal gravitation is the result of a piecemeal generalization. Newton’s argument for universal gravitation is a careful reasoning process, in which we step-by-step generalise data. This careful proceeding from particular events to “lesser Axioms” and then finally to universal axioms corresponds to Bacon’s methodized idea of induction. This sensitivity of establishing universal axioms *via* partial generalizations and the importance attributed to further testing the inferred principle in the synthetic part of science is clearly Baconian of inspiration. Both Bacon and Newton sought to circumvent the simplistic method of enumerative induction.

Although there exists no explicit *locus* where Newton pays his respect to Bacon’s method of induction, and Newton does not cast his arguments in close alignment to Bacon’s tables, Newton’s practice is clearly vivified by the Baconian spirit of careful, methodized induction. Newton put to practice what Bacon preached. In this respect, Newton was surely indebted to Bacon. There is a moral to this story as well: we should not restrict ourselves to the explicit utterances of a scientist (and,

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[11] In Newton’s famous 1672 optical paper (which contains the *experimentum crucis*), he eliminated all other possible causes of the appearance of an oblong form produced by refraction through a prism by showing that these putative causes were incompatible with observation. Athanasios Raftopoulos has called this procedure “the elimination through controlled experiment”. See Raftopoulos, 1999.

by extension, of philosophers), but also look at their actual *praxis* which sometimes reveals more than explicit utterances.

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