Indian Journal of History of Science, 43.4 (2008) 589-630

SCIENTIFIC RESEARCH PAPERS IN THE *PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY OF LONDON*, 1665–1800: THE DEVELOPMENT OF PHYSICS IN THE FOOTSTEPS OF SIR ISAAC NEWTON

S. Ducheyne*

(Received 7 May 2008; revised 12 September 2008)

For who's the wiser for knowing that the Bones of a dead Fish have been dug up, or where?[1]

In this paper an *internal* and *external* quantitative and qualitative analysis is provided of scientific papers on physics published by *Philosophical Transactions* of the Royal Society between 1665 and c. 1800. The paper consists of two parts: the first part deals with the quantitative aspects (= the *descriptive* account, on which a lot of emphasis has been laid in existing studies, but not treated in full detail nor set up as to allow trans-disciplinary studies); the second part on the methodological shifts in physics and the topics (= the *systematic* or *qualitative* counterpart). The primary focus will be on Newtonian physics.

Keywords: Royal Society, Philosophical Transaction, Isaac Newton, Scientific journals, Seventeenth-century science, Eighteenth-century science.

Introduction

The Royal Society[2] was established on 28 November 1660 (Fig. 1). At Gresham College "a Colledge for the Promoting of Physico-Mathematicall Experimentall Learning" was established by twelve members-to-be. "*Nullius in verba*" was the Society's motto. The most notable members were, Robert

* Centre of Logic and Philosophy of Science, Ghent University, B-9000 Ghent Belgium. E-mail: SteffenDucheyne@UGent.be

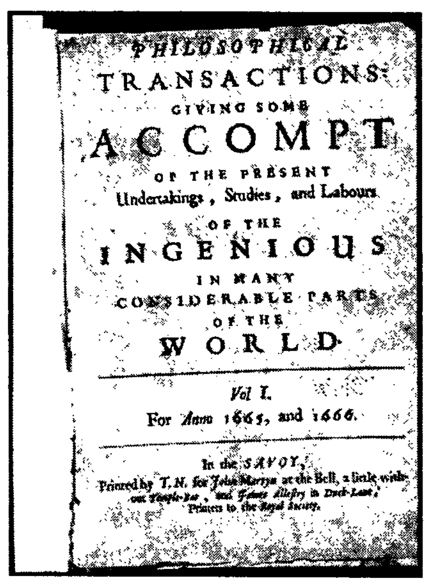
Boyle, William Brouncker, Robert Moray, John Wilkins and Christopher Wren.[3] In the first volume of the *Philosophical Transactions*, the editor Henry Oldenburg wrote on the aim of the *Transactions* in the introduction dedicated to the King, as follows:

> The Great God prosper You in the Noble Engagement of Dispersing the true Lustre of his Glorious Words, and the Happy Inventions of obliging Men all over the World, to the general Benefit of Mankind (...).[4]

The journal's subtitle was: "GIVING SOME ACCOMPT OF THE PRESENT Understanding, Studies and Labours OF THE INGENIOUS IN MANY CONSIDERABLE PARTS OF THE WORLD" (Fig. 2). In the preface to volume 1 Oldenburg wrote the following in response to Mr. Cowley who despised the New Philosophy:

> Is it New Philosophy, to inquire diligently the things that are; I mean, To know how the World was made, and the operation of the Elements; the beginning, ending, and midst of Times; The Alterations of the Turning Sun, and the Change of Seasons; The Circuit of Years, and the Position of Stars; The natures of Living Creatures the Furies of Wild Beasts, and the reasonings of Men, the Violence of Winds, and the Motions of the

Fig. 1. Title page of Thomas Sprat's *History of the Royal Society of London*. On the left Lord Brouncker, in the centre a bust of King Charles II, and on the right Lord Verulam, Francis Bacon.



PHILOSOPHICAL TRANSACTIONS: GIVING SOME ACCOMPT OF THE PRESENT Undertakings, Studies, and Labours OF THE INGENIOUS IN MANY CONSIDERABLE PARTS OF THE WORLD.

Vol I.

For Anno 1665, and 1666.

In the SAVOY,

Fig. 2. Front-cover of the first volume of the *Philosophical Transactions*.

> Seas, the diversities of Plants, and the virtues of Roots; and all such things, as are either Secret or more manifest? [5]

Such inquiries have been "practiced and countenanced by the Best of Men"[6]. Moreover knowledge stems from knowledge of "the Magnitude, Figure, Situation, and Motion of them, which are all mechanically to be considered, or we come short of a Satisfactory Information"[7]. The Society was soon to be accompanied by its first volume of the *Philosophical Transactions* for the years 1665/1666 (the *Journal des Sçavans* had by that time already printed its first volume two months earlier on 5 January 1665), although the Society only assumed official responsibility from 1751.

Remarkably, few studies on the *Philosophical Transactions* exist[8] and, to the best of the author's knowledge, no long-term bibliometric fine-tuned studies – as the author shall now pursue – are at hand.[9] Much badly needed rhetorical and detailed factual knowledge has been provided on these matters, but on the *differentiation of research topics* and especially on *relevant qualitative changes in physics* the literature remains silent. In the essay at hand, we shall therefore focus on the latter.

The first series of the *Philosophical Transactions* (1665-1678/9) contained vol 1-12. After four years of non-publication – during this interval, Robert Hooke was requested to publish the *Philosophical Collections*, which focussed on scientific research done abroad and which we shall not include in this survey – the second series of the *Philosophical Transactions* (1682/3-1775) continued and contained vol 13-65. In 1776 the journal was renamed "*Philosophical Transactions of the Royal Society of London*" (1776-1886) and contained vol 66-177. In 1887 this journal was split into *Philosophical Transactions of the Royal Society of London A* (1887-1895), mainly dealing with the physics (applied and theoretical), mathematics and chemistry and into *Philosophical Transactions of the Royal Society of London B* (1887-1895) dealing with topics of "biological character". These will not be considered here.

In the essay at hand, the author seeks to investigate the first series of the *Philosophical Transactions* from vol 1 to 65 (because the early days can be used to point to relevant changes *qua* methodology and the topics covered in the pre- and post-Newtonian period) up to volume 140 of the *Philosophical Transactions of the Royal Society of London* published in 1850. The motivation for this is the following: roughly after 1850 the centre of scientific attention shifted mainly to theoretical electro-magnetism and in classical mechanics no fundamentally new discoveries were made, only further corroborations and elaborations of Newtonian mechanics. Therefore in what follows we shall focus on Newtonian topics such as: astronomy, mechanics, optics and the study of small scale accelerative and repellent forces. We shall pay attention special attention to the methodology of theoretical and, to a lesser extent, applied Newtonian physics during this period. Although we shall quantitatively describe papers from 1665 to 1850, we shall deal with methodological issues up until the early nineteenth century. In the early eighteenth century Newton's name was sometimes mentioned, but his optical work was under severe attack. After the early nineteenth century Newton's theories are hardly mentioned at all. Of course, this *terminus* is somewhat artificial as it is difficult to draw clear lines in the appearance of the *Philosophical Transactions* – and in the history of science in general, for that matter. As it is the author's aim to focus on Newtonian mechanics, we shall not further discuss the evolution of later volumes.

One matter of terminology: henceforth, we shall use the name "*Philosophical Transactions*" to cover both the *Philosophical Transactions* as well as the *Philosophical Transactions of the Royal Society of London* – unless possible confusion is lurking. We shall provide the relevant bibliometric data that will serve as the point of departure not only for the author's own research chronology but also for the readers' lecture.

It is only recently that scholars have studied the scientific research paper as a genre. According to Alan G. Gross, Joseph E. Harmon and Michael Reidy, the seventeenth-century research paper is characterized by the inclusions of personal accounts, little or no references, and the frequent use of evaluative language.[10] Dwight Atkinson adds to that acts of witnessing, indexes of humility and modesty, tendency towards digressions and elaborate politeness ("*Sir*").[11] In the eighteenth century, natural philosophy meant Newtonian physics.[12] Newton's research was exemplary[13] for scholarly writing: papers now included headings, figure captions, numbering systems for citations and visuals, introductions contextualizing the research problem and conclusions that clearly stated and contextualized a new knowledge claim.[14] Atkinson further notes that "the research model modelled by Newton appears to have resulted in longer and more elaborately organized articles, such as three very long, mathematically oriented by J.T. Desaguliers on the shape of the earth"[15]. In the nineteenth century, as the professionalism in science became a striking feature, title and author credits, equations separated from text, visuals provided with *legenda*, and standardisation of citations, format, style, terminology (*cf.* William Whewell) and position became characteristic of the scientific research paper.[16]

Such studies should be combined by studies of the shifts in scientific methodology, in Newtonian physics.

PART I

A BIBLIOMETRIC ANALYSIS OF ALL DISCIPLINES

In order to situate and study the evolution of publications on theoretical and applied mechanics, a bibliographic *cum* bibliometric list, containing the quantitative data of scientific papers published in diverse disciplines, is a good starting point. The author's aim is first to point to the quantitative changes in the scientific output on theoretical physics. We shall also deal with the qualitative changes, i.e. changes in the topics and methodology employed: this is the *internal study* of these publications (as we shall see in the following sections). Here rhetorical strategies and styles of presentation will be neglected, as the focus is really on the technical and methodological matters.

In order to estimate the weight of theoretical Newtonian physics-mechanics *vis-à-vis* other scientific disciplines (i.e. to establish an *external study* of the publications in this discipline) research papers on these matters are compared quantitatively with publications in other disciplines.

We have followed some conventions: to divide the quantitatively internal and external data per 5 vols – as by year several gaps would arise, since during some years no volume appeared and a volume often contained several years together. This periodization allows for sufficient fine-tuning. 140 vols are thus dealt with in 28 intervals. Book reviews and short letters are not included here – although the author has consulted them – prefaces and "Epistles Dedicary" will be used.

All papers were classified in seven categories: (1) earth sciences (including: crystallography, geology, geography, meteorology, mineralogy, and navigation), (2) chemistry, (3) theoretical physics (including: astronomy, electricity, hydrostatics, magnetism, mechanics, and optics), (4) applied physics (including: engineering, instruments, gunnery, machinery, and metallurgy), (5) mathematics (also including musicology), (6) biology (including: anatomy, animal kingdom, biology, botany, entomology, and medicine) and (7) humanities (including: archaeology, architecture, calendar chronologies, collections, dictionaries, economy, history, language, manuscripts, numismatics, politics, and population).

The Data

	1-5	**6-10**	**11-15**	**16-20**
Earth Sciences	49	30	40	57
Chemistry	8	13	5	16
Theoretical Physics	36	71	41	48
Applied Physics	7	4	21	19
Mathematics	20	6	1	7
Biology	99	58	60	88
Humanities	0	1	11	24
Articles Published	241	183	179	259
	21-25	**26-30**	**31-35**	**36-40**
Earth Sciences	33	36	35	27
Chemistry	33	14	88	19
Theoretical Physics	44	71	18	86
Applied Physics	15	3	18	30
Mathematics	22	14	12	7
Biology	177	79	135	109
Humanities	31	23	8	13
Articles Published	355	240	314	291
	41-45	**46-50**	**51-55**	**56-60**
Earth Sciences	53	118	48	57
Chemistry	16	15	8	13
Theoretical Physics	103	68	66	53
Applied Physics	19	31	21	10
Mathematics	7	8	7	10
Biology	173	133	67	50
Humanities	30	37	11	15
Articles Published	401	410	228	208

	61-65	66-70	71-75	76-80
Earth Sciences	67	27	19	23
Chemistry	21	6	17	18
Theoretical Physics	65	24	51	16
Applied Physics	34	23	18	6
Mathematics	14	9	6	7
Biology	89	30	17	14
Humanities	28	5	3	25
Articles Published	318	124	131	109
	81-85	**86-90**	**91-95**	**96-100**
Earth Sciences	18	13	8	21
Chemistry	20	14	18	20
Theoretical Physics	14	13	10	18
Applied Physics	9	3	2	6
Mathematics	2	2	5	10
Biology	11	16	17	39
Humanities	9	1	0	0
Articles Published	83	62	60	114
	101-105	**106-110**	**111-115**	**116-120**
Earth Sciences	8	18	2	12
Chemistry	13	3	11	1
Theoretical Physics	16	11	38	27
Applied Physics	4	9	10	8
Mathematics	6	7	1	3
Biology	15	20	7	4
Humanities	2	1	1	0
Articles Published	64	69	70	55
	121-125	**126-130**	**131-135**	**136-140**
Earth Sciences	8	12	11	13
Chemistry	1	2	3	11
Theoretical Physics	3	22	5	10
Applied Physics	1	1	2	1
Mathematics	0	1	0	3
Biology	1	6	5	19
Humanities	0	0	0	12
Articles Published	14	44	26	69

Graphical Representation and Discussion of the Data

The x-axis refers to five-volume intervals; the y-axis refers to the number of publications in a discipline like Earth sciences, chemistry, Theoretical Physics etc. (Convention).

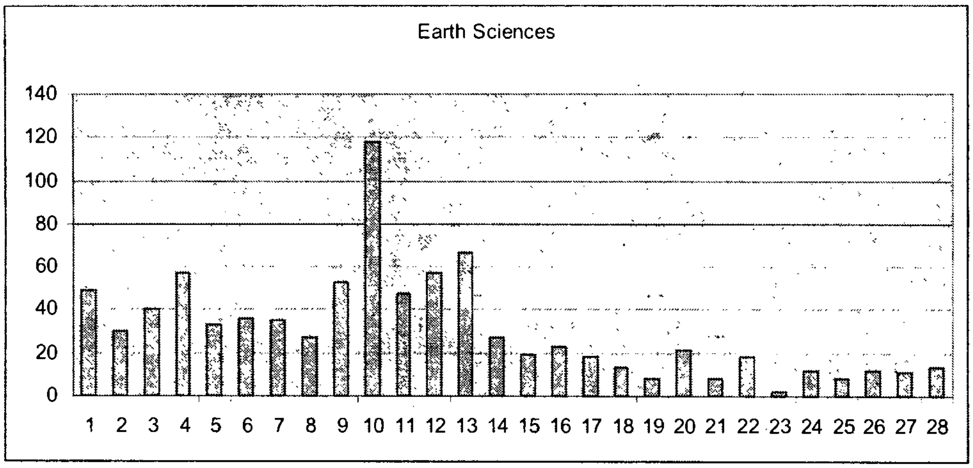


Fig. 3. Earth Sciences. Papers in this category were fairly represented in the first 65 vols. Later on the number of publications remained stable. The topics discussed did not change significantly. Typical subjects were: geographical descriptions, reports on tides, meteorological, geological and mineralogical observations, observations on mines, springs and lakes. In vols 45-50 (i.e., between 1750 and 1757) there was increasing activity in the earth sciences. In this period a considerable meteorological matters were reported on, especially observations of earthquakes and thunderstorms. The famous earthquake in Lisbon contributed to this increased interest on this subject.

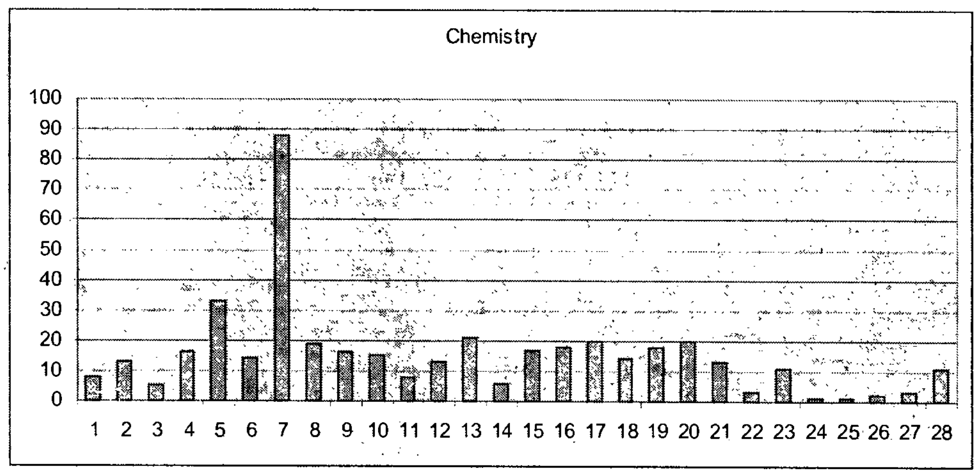


Fig. 4. Chemistry. With the exemption of two peaks in volumes 21-25 and 31-35, the number of papers in this category remained fairly stable. During 1720 and 1728 there was an increase of chemical research. Typical topics in this period are investigations on specific weight of materials, cohesion, composition and properties of substances (water and wine), and especially the properties of salts.

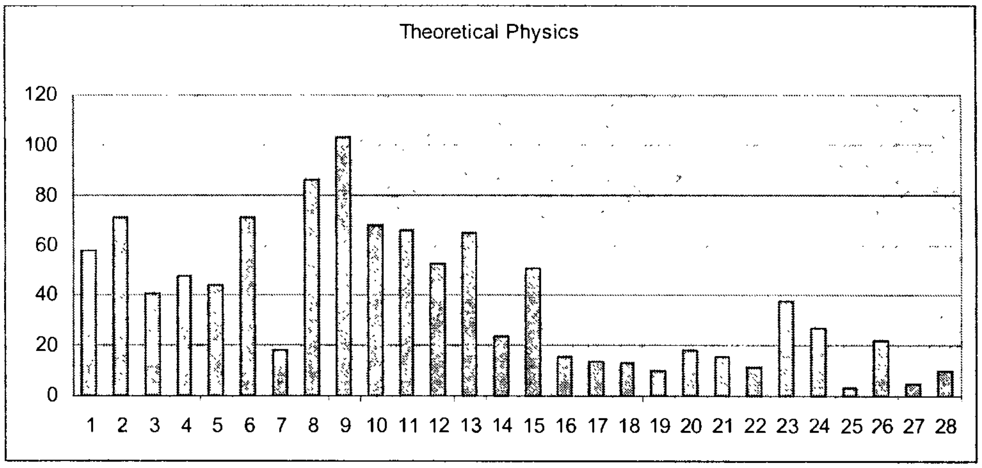


Fig. 5. Theoretical Physics. From the first volume to 1785 there was a high number of publications in this area until 1785 (hereafter a nearly constant and respectable amount of output). The most studied subjects were not surprisingly mechanics and astronomy. We shall discuss these topics in more detail in what follows.

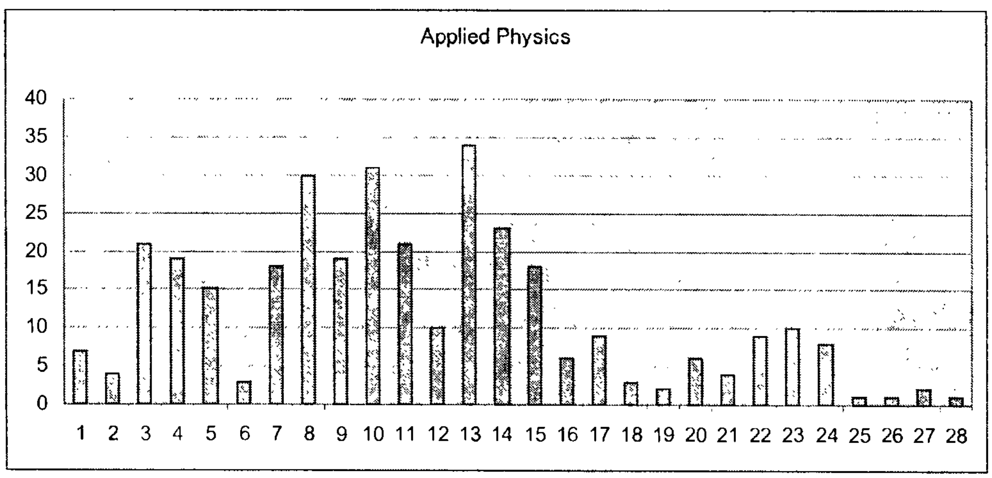


Fig. 6. Applied Physics. Frequent publications appeared in volumes 11 to 75. Thereafter the number of papers remains fairly constant. As one can see, the number of publication in the applied sciences mirrors that in theoretical science. There was thus a close connection between applied and theoretical physics. Closer inspection shows that the pre-1785 papers mostly reported on new measuring or observational devices directly relevant for theoretical physics in the same period. Most engineering related topics were technological applications of mechanical principles.

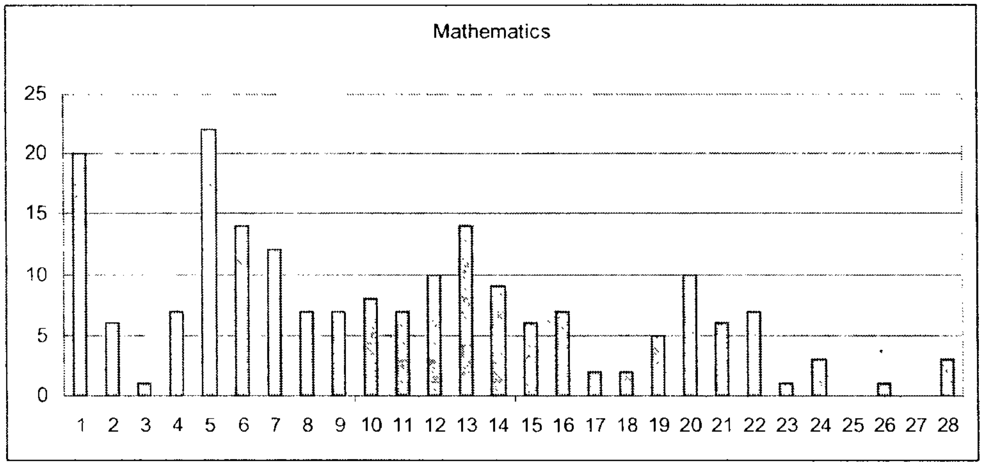


Fig. 7. Mathematics. Papers in this category follow a decaying wave-like pattern with peaks is volumes 1 to – i.e, from 1665 to 1670 – (where geometry, the study of curves, hyperboles occupied centre-stage), volumes 21-25 – i.e, from 1699 to 1707 – (where tangents and quadrature occupied centre-stage), volumes 61-65 where logarithms and geometrical problems in astronomy occupied centre-stage), and volumes 96-100 – i.e, from 1806 to 1810 – (where analytical mathematics, the study of tangents, summation of infinite series, and logarithms occupied centre-stage).

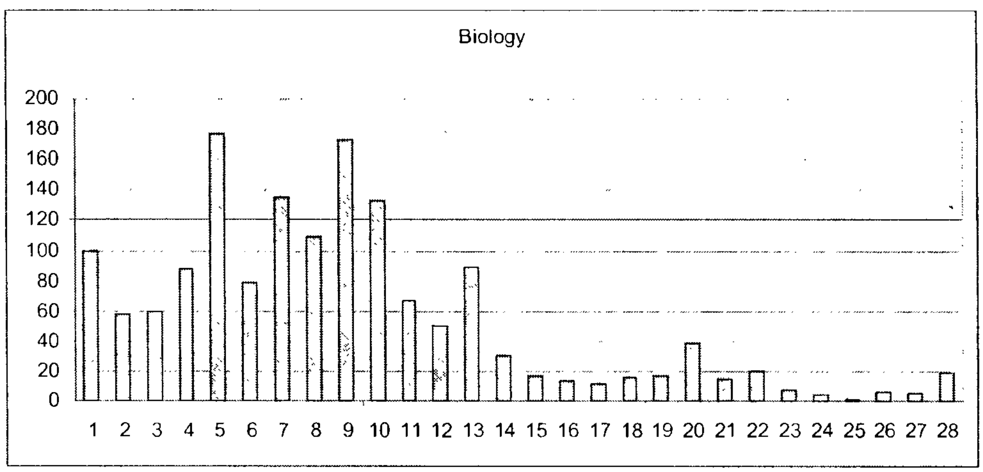


Fig. 8. Biology. Biological papers were highly published (nearly reaching a peak of 180 papers in volumes 21-25). Afterwards, i.e. after volume 65 (1775), they decreased dramatically. Especially popular were descriptions of fauna and flora, medicine and anatomy.

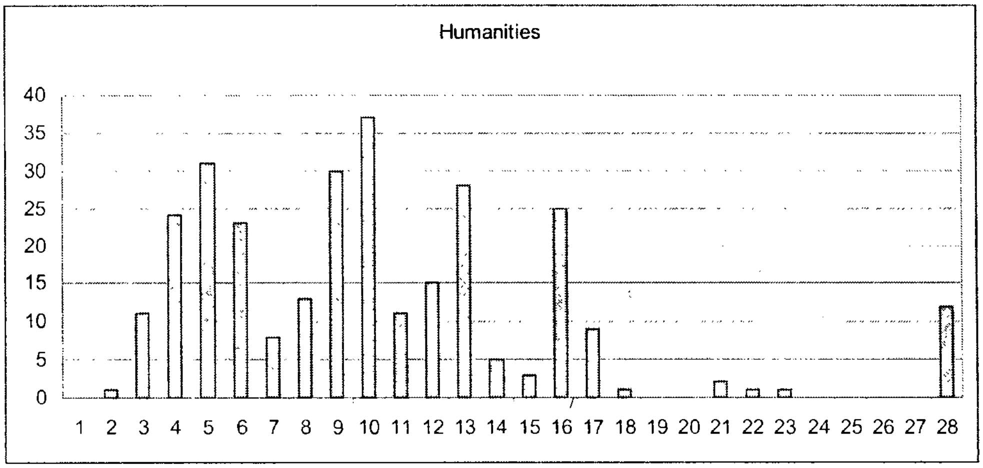
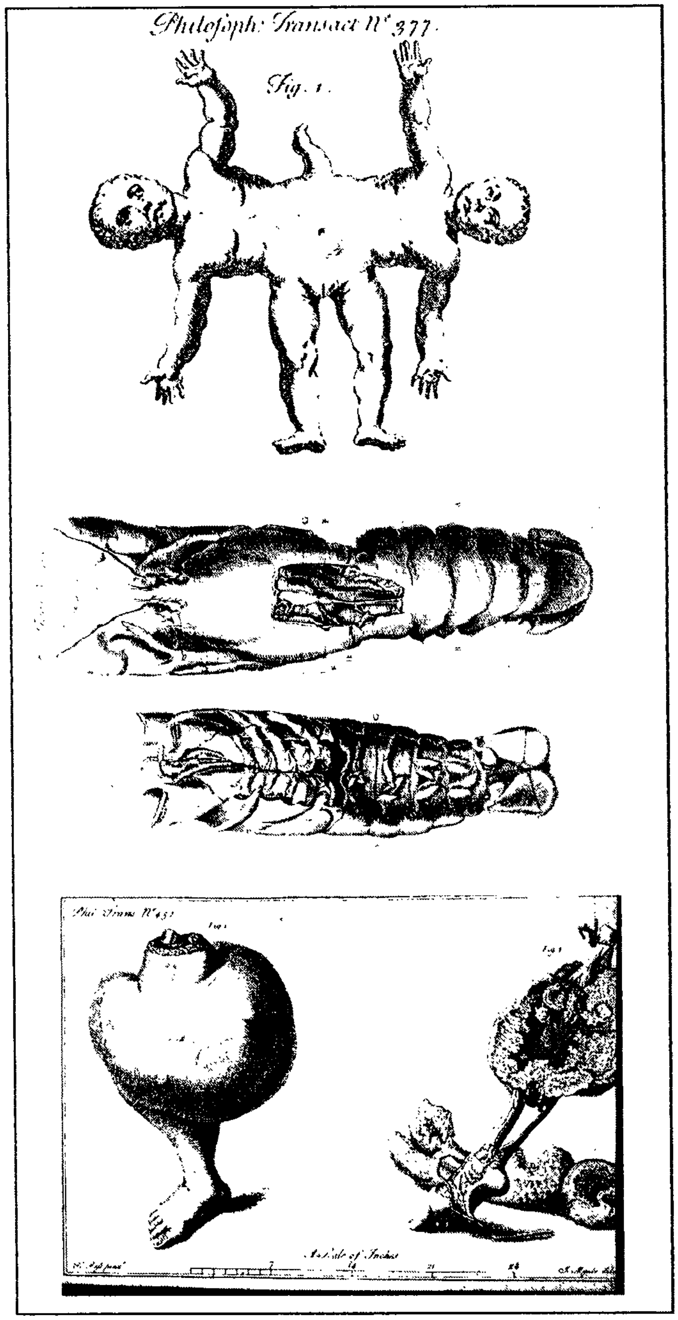


Fig. 9. Humanities. In the humanities there was a decaying trend after volume 1795. The reason for this decay is obvious: the Royal Society began to focus increasingly on the exact sciences.

Summary: Together with earth sciences and biology, theoretical physics was one of the most represented disciplines in the *Philosophical Transactions*. It was one of the crown disciplines at the time. We will only deal here with theoretical physics. Needless to say, that the data presented in the section is highly relevant to scholars wishing to investigate other disciplines.

A Lacuna in the Present Literature

In the early days, under Hans Sloane's presidency, of the *Philosophical Transactions* theoretical physics appeared amongst anecdotic narrations, reports on the downright bizarre and even proofs for divine providence. For instance, John Arbuthnott argued that "Polygamy is contrary to the Law of Nature and Justice, and to the Propagation of Human Races; for where Males and Females are in equal number, if one Man takes Twenty Wives, Nineteen Men must live in Celibacy, which is repugnant to the Design of Nature; nor is it probable that Twenty Women will be so well impregnated by one man as by Twenty"[17]. In volume 33 the case of a man is described who suffered from bowel problems and put a fork "up the Anus, that was afterwards drawn out the Buttock" whereby it was noted by the Physician Robert Payne that "the End of the Handle was besmeared with the Excrement".[18] This therapeutic procedure was not without risk, Payne added: "unfortunately it slipt up so far, that he could not recover it again". Papers



Figs. 10-11 & 12. Curiosities taken from early volumes of the *Philosophical Transactions*. Fig. 10: A Siamese twin, Fig. 11: a hermaphrodite lobster and Fig. 12: a severe intumescence.

like these surely inspired William King's famous satire of the *Philosophical Transactions*.

According to Heilbron, Newton's presidency meant "a revival and transformation of the demonstration experiments"[19]. Much of the research papers were, as. Heilbron notes, either extensions (in subjects such as optics (Hauksbee), electricity (Hauksbee), ether (Hauksbee, Desaguliers), capillarity (Hauksbee, Taylor, Jurin), magnetism (Hauksbee, Halley, Stephens, van Musschenbroek), and measurement (Derham, Hauksbee, Desaguliers)) or defences of the physics embodied by the *Principia* and *The Opticks*.[20] This study will further confirm this conclusion.

PART II

QUALITATIVE ANALYSIS OF THE DATA: THE METHODOLOGICAL TRENDS IN RESEARCH PAPERS ON THEORETICAL PHYSICS

In this part, it is planned to focuss the following branches of physics: astronomy, mechanics, optics and small-scale attractive and repellent forces.

Astronomy

In two papers Adrien Auzout, who also wrote on the possibility of life on the moon[21], reported on his studies of the comets.[22] Auzout "a *French* Gentleman of no ordinary Merit and Learning" had by careful observation and timekeeping shown that comets follow regular paths and predicted the places where they would appear. This was never undertaken:

> [...] by any *Astronomer*, all the World having been hitherto persuaded, that the motions of *Comets* were so irregular, that they could not be reduced to any Laws, and men having contended themselves, to observe exactly the places, through which they pass; but no man, that he knows, having been so bold as to venture to foretel the places, through which they should pass, and where they should cease to appear [...][23]

Auzout was one of the first who demonstrated that comets exhibit regular and mathematically describable behaviour. Comets were no longer irregular appearances, they obeyed law-like patterns. It was also noted that this "Philosophical Prophet" considered that "although his Method should be very exact, *if there be not at hand Instruments big enough, and Globes good* *enough to trust to*, nothing can be done perfectly in these kind of Predictions".[24] According to Auzout, scientific theories were good, nearly exact, but probable representations of reality. Johannes Hevelius[25] investigated the physical causes of the generation of comets, which according to him described conical trajectories. [26] The matter of comets consists of ether, i.e. condensed air. which can only be cast out by the sun so that enough matter is produced that one or two comets are appear annually.[27] This was an important step towards Newtonian physics: comets which were seen as freak-phenomena followed regular patterns.

Not surprisingly, in early astronomy the stress lay mainly on new observations and correspondingly observers (such as Ismaël Bullialdus, Giovanni D. Cassini, John Flamsteed, Edmund Halley, Robert Hooke, Christiaan Huygens) published their discoveries in the *Philosophical Transactions*.

In mathematics related to physics, Jacob Stirling noted that Newton's "methodus procedenti per quantitatum nescentium & evenescentium rationis primas & ultimas, seu si ita loqui liceat, per quantitatum coincidentium differentias infinite parvas" [28] was highly useful in the domain of astronomy.

After the publication of the *Principia* in 1687, many followers joined forces. In his two papers on the figure of the earth, J.T. Desaguliers noted that he wished to deduce the figure of the earth by deducing it from Newton's principles.[29] He concluded his first paper as follows:

> Tho' Sir *Isaac Newton*, in his *Principia*, has not endeavour'd to give the Cause of Gravity, or to determine whether it be owing to an impulse or not; yet he has shewn what its Effects and Laws are, from plain Experiments made by others and himself, From the Laws of Gravity, and form the Observation of a Comet, he has deduced the Annual Motion of the Earth; and it must have a Diurnal Motion, if it has an Annual one, otherwise, it will not agree with the *Phœnomena*.[30]

In the late eighteenth century, occasionally research was done that can be considered of providing new additions to Newtonian gravitation. For instance, William Herschel, contributed intensely to astronomy, wrote on the earth's diurnal motion.[31]

Mechanics

Edmund Halley's paper on the descent of heavy bodies and projectiles contained a brief "but fully handled" account of these matters.[32] He began by rebutting Descartes'[33] and Vossius' proposals. He also clearly indicated that the efficient cause of gravity is unknown and that when we assert that it is sympathical attraction we are "far from explaining the *Modus* that is a little more, than to tell us in other terms, that *heavy bodies descend*, because they descend"[34]. He therefore prefers to talk about the "appearances" of gravity. These have been discovered by Newton.[35] The final cause of gravity is known namely that "all the Celestial Bodies are kept from dissolution"[36]. In the remainder of his paper, he proved 6 propositions which are basically Galileo's theory of bodies in free fall and projectiles – strangely he does not mention that they are derived completely from Galileo – *en passant* he mentioned his name together with Torricelli's and Huygens'.[37] He discussed the proportionality of speed and time, the proportionality of distance and the square ratio of the times, the Mertonian rule, the amount of descent of free falling bodies in one second (16 feet and one inch; this value was first calculated by Huygens), the parabolic trajectory of projectiles[38], and the fact that the horizontal distances of projectiles made with the same velocity are as the sines of the doubled angles of elevation.[39] Finally, he considered the mathematical part of gunnery wherein he shows that, as Galileo did, that under a 45° angle a projectile will traverse the largest distance. In two other papers he considers (Huygens') cycloid.[40] He also presented Newton's equilibrium-theory of the tides[41]: "From this principle, as a necessary Consequence, follows the Sphærical Figure of the Earth and Sea, and of all the other Cælestial Bodies: and tho' the tenacity and firmness of the Solid Parts, support the inequalities of the Land above the Level; yet the Fluids, pressing equally and easily yielding to each other, soon restore in *Æquilibrium*, if disturbed, and maintain the exact Figure of the Globe"[42]. Again he stressed that he only considered the appearances of gravity.[43] Gravity is the general cause of the tides but "it remains now to shew how naturally this Motions account for all the Particulars that has been observed about them; so that there is no room left to doubt, but that this is the true cause thereof"[44]. He concluded that "the whole appearance of these strange tides, is without forcing naturally deduced from these Principles, and is a great Argument of the certainty of the whole *Theory*"[45]. Finally, Brook Taylor wrote a piece on the centre of gravity[46] and Edward Waring, one on how to calculate decomposition of attractive forces.[47]

David Gregory's piece provided an account of the catenary, on which Huygens, Leibniz and Bernoulli have discovered its mathematical properties, by means of Newton's method of fluxions.[48] In this paper he wanted to show how the catenary can be accommodated by "ope Methodi Newtonian*æ* Geometreis hodie familiaris, fluxiones è fluentium".[49] An anonymous writer noted on the area law: "Sublimiorem vero postulat Geometriam, ad ostendendum quam ob causam [a *vis centripetalis*] hoc ita se habeat, quodque aliter non posit. Hoc sempiternam celeberrimi D. *Newtoni* nostri gloriam reservatum est.".[50]

John Keill offered an analytical method to the Newtonian solution Kepler's area law. He noted: "mihi videtur esse illa methodus quam tradit Dominus Newtonus in Principiis, pag. 111 & 112. Edit. 1*mæ*, quae fere similes est ei qua ex aequationibus affectis extrahunt radicem Analyticae" and added that both solutions are drawn "secundum vera mutuum leges, & non ex fictis hypothesibus"[51].

J.T. Desaguliers was an ardent defendant of Newton's optical and mechanical theories and wrote nearly 60 articles in the *Transactions*. Here we shall focus on the mechanical material.[52] In one paper Desaguliers defended the Newtonian view that the quantity of forces is proportional to m and v (and not to m and v^2, as Leibniz claimed) by several experiments.[53] One illustration of such experiments proceeds as follows: let a balance of which the fulchrum is so divided that the distance of the first brachium is ¼ of that of the second (a weight 100 pounds is attached to the first brachium and to the second brachium a weight of 25 pounds). In this case the fulchrum (at C) is in equilibrium (by the law of the lever: $w_1 \cdot d_1 = w_2 \cdot d_2$., i.e. 100 . ¼ = 25 . 1). Now, assuming that the quantity of forces is proportional to m and v^2, "the twenty five Pound Weight should have been suspended at D, only twice as far from C, as the Weight at A"[54,55].

Three other papers deserve to be mentioned in this survey. In 1726-1727 Benjamin Robins demonstrated Proposition 11 of Newton's treatise on the quadratures.[56] In 1761-1762 Charles Walmesly published a Newtonian account of the irregularities between planets, which are not due to the elliptic trajectories of the planets, by focussing on the mutual attraction between the earth and Venus.[57] Finally, in 1777 John Landen published a new theory of rotary motion, initially applicable to cylinders and spheroids.[58,59]

Optics

No doubt the most important work in optics can be found in Newton's first optical paper to the Royal Society, *New Theory about Light and Colors* (1672)[60], which contains his first enunciation of his theory of light. 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 – but has an oblong form. According to the received view, we can expect an elongation, except for the position of minimal deviation. If one assumes that all rays are equally refrangible, then in the position of minimal deviation (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. This position presupposed but not mentioned by Newton in his paper. It is mentioned in *The Opticks*. This confused several natural philosophers.[61] The second experiment is Newton's famous *experimentum crucis*.

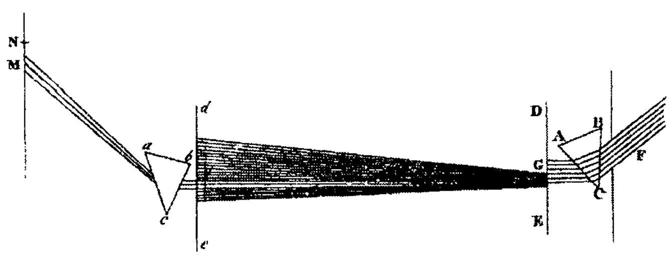


Fig. 13. Newton's *experimentum crucis*.

Newton took two boards and two prisms. 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.

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. 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. 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 to their degrees of refrangibility, transmitted toward divers parts of the wall.[62]

> 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.[63]

The *experimentum crucis* was later re-defended by means of candles by Desaguliers.[64] 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). 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.[65] 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. White light consists of a heterogeneous mixture of different rays with an inherent degree of refrangeability. Newton could indeed understandingly claim that to every colour there corresponds a specific degree of refrangibility, but not that white light is a heterogeneous aggregate. Hooke claimed that his pulse hypothesis could equally account for the experimental results without conceding the heterogeneity of white light. 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 later reintroduced in the nineteenth century: Gouy demonstrated that white light can be represented as the superposition of an infinite number of waver 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. 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). What are the hidden assumptions used to arrive at the conclusion that lights *consists* of rays differently refrangible? Newton believed that 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. 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. (They can also be recombined. If a lens is placed after a prism, it will make the rays converge again at a certain (white point) point.) 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.[66]

We conclude that Newton provided a mechanism that explained the oblong form NM in minimal deviation: the structural heterogeneity of white light. These early papers on optics would be Newton's last papers for the *Transactions*.

Later Newton's *experimentum crucis* was replaced by a more simple experiment. J.T. Desaguliers "so easy to be made, that by it those who want the *Apparatus* (or are unwilling to be at the pains) to make the *Experimentum Crucis*[67], may at any time satisfy themselves on the Truth of the fore-mention'd Doctrine"[68]. A candle is placed in front of a "Chimney Looking Glass" and an observer looks at the glass from points close to the candle. These points are equidistant. The observer will notice that with two eyes open the spectrum of image of the candle will appear double, but not so that an intermediary colour will be seen; when the observer looks at the image of the candle only one colour will be seen.[69] This suffices, says Desaguliers, to prove the truth of the doctrine of the heterogeneity of white light.

In the early nineteenth century scholars pointed to several failures in Newton's optics. After Newton died his optical theory occasionally was the target of criticism.[70] By the early nineteenth-century some flaws began to be recognised.[71] Thomas Young noted that: "Those who are attached to the Newtonian theory of light, or to the hypotheses of modern opticians, founded on views still less enlarged, would do well to endeavour to imagine any thing like an explanation of these experiments, derived from their own doctrines; and, if they fail in the attempt, to refrain again from idle declamation against a system which is founded on the accuracy of its application to all these facts, and to a thousand of a similar nature."[72]. To following papers deserve further mentioning. David Brewster wrote an article on polarization of light in which he noted that Newton's error lay in denying "the construction of an achromatic telescope to be incompatible with the known principles of optics"[73]. John Herschel reported on "the very considerable from the succession of colours in thin laminæ, as observed by Newton, which many crystals exhibit when cut into planes perpendicular to one of their axes"[74].

Small-scale Attractive and Repellent Forces

Francis Hauksbee reported frequently on experiments on electricity and magnetism and gave much inspiration to Newton's own research on these matters especially on his study of small-range attractive and repellent forces.[75] It is abundantly clear from both published work as well as from manuscript material that Newton sought to (but, as we will see, also failed to) experimentally demonstrate, i.e. to rigidly deduce from phenomena according to his own, highly developed, methodological standards, the forces of magnetism and electricity[76], short-range attractive and repulsive forces, and the causes producing fermentation, nutrition, corruption and generation of organisms, putrescence, muscular movement and perception[77], refraction, reflection and, finally, diffraction.[78] These rather "speculative" experiments were never included in the *Principia*, the work "which Newton was the most anxious to make immune from attack"[79] and are merely hinted at in the General Scholium.[80] However, a systematic survey of the subtle changes in the observations or experimental set-ups which Newton, at some point in between 1687-1713, intended to be included in the *Principia*, and by means of which he sought to establish and study the other non-gravitational forces in nature, has, to the best of my knowledge, not been undertaken. This is precisely the goal of this section. This survey shows that most attention went to Newton's non-gravitational forces and not so much to further investigations of the force of gravity. Therefore we shall not further address Newton's articulation of gravity as a cause and the famous gravitational ether issue.[81]

In order to understand Newton's various attempts in this area it is necessary to consult (1) the observations and experiments he referred to in the suppressed *Preface* and *Conclusion* to the first edition of the *Principia*, (2) the draft versions of the General Scholium (especially the A-version and, to lesser extent, the C-version), (3) and the text as it appeared in the second and third edition of the *Principia*. Newton's choice to suppress this material can be traced from these manuscripts.

We shall start chronologically with the *Preface* written in 1687. Newton began by expressing his hope that the other (non-gravitational) phenomena would be derived from mechanical principles by the same mode of reasoning (as the force of gravitation) [ex Principijs Mechanicis eodem argumentandi genere derivare liceret[82]]. He distinguished between three classes of fundamental forces: gravity, magnetism and the force producing attractive and repellent forces between particles at small distances.[83] In order to render the force of the latter type more plausible, Newton gave a cornucopia of phenomena that served the purpose of illustrating this force. Newton stated that attractive and repellent forces at small distances accounted for various chemical reactions and for the cohesion of bodies, and that they also explained why bodies are "hard, soft, fluid, elastic, malleable, dense, rare, volatile, fixt; [capable of] emitting, refracting, reflecting or stopping light"[84]. In trying to justify his claim, he fiercely relied on Nature's causal parsimony[85] and *speculated* that the motions of smaller bodies could be explained by forces "just as the motions of larger bodies are ruled by the greater force of gravity":

> For if Nature be simple and pretty comfortable to herself, causes will operate in the same kind of way in all phenomena, so that the motions of smaller bodies depend upon certain smaller forces just as the motions of larger bodies are ruled by the greater force of gravity. It remains therefore that we inquire by means of fitting experiments whether there are forces of this kind in nature, then what are their properties, quantities and effects.[86] For if all natural motions of great or small bodies can be explained through such forces, nothing more will remain to inquire the causes of gravity, magnetic attraction and the other forces.[87]

Essentially Newton was arguing for the usage of transduction (see *infra*) in natural philosophy. Here we also find Newton setting the agenda for the future study of natural philosophy. Newton distinguished between four experimental issues that need to be addressed in order to complete the study of the fundamental forces in nature: (a) the investigation of whether there are forces of a certain type, (b) the investigation of their effects, (c) their properties, and (d) their quantities.

However, to explain these short-range forces is more problematic than to explain universal gravitation. This is more apparent from Newton's suppressed *Conclusion*. Here Newton's tone changed and he now hinted at some of the difficulties an experimental treatment of such short-range forces poses. Newton began the *Conclusion* by observing that there are plenty of other motions than those caused by the force of gravity:

> Hitherto I have explained the System of this *visible world* [Mundi aspectabilis], as far as concerns the *greater motions which can be easily detected* [facile sentiri possunt]. There are however innumerable other local motions which *on account of the minuteness of the moving particles*

> *cannot be detected* [ob parvitatem corpusculorum moventium, sentiri nequeunt], such as the motions of the moving particles in hot bodies, in fermenting bodies, in putrescent bodies, in growing bodies, in the organs of sensation and so forth. If any one shall have the good fortune to discover all these, I might almost say that he will have laid bare the whole nature of bodies so far as the mechanical causes of things are concerned. I have least of all undertaken the improvement of this part of philosophy. I may say briefly, however, that nature is exceedingly simple and conformable to herself [natura valde simplex est et sibi consona]. Whatever reasoning [Quam rationem] holds for the greater motions [in majoribus motibus], should hold for lesser ones as well [in minoribus]. The former depend upon the greater attractive forces of larger bodies, and I suspect that the latter depend upon the lesser forces, as yet unobserved, of *insensible particles* [particularum insensibilium].[88]

Newton began by reiterating his belief in transduction. One obvious stumbling-block for applying such mode of argumentation is that, in this case, *not only the forces which produce these "lesser motions" cannot be observed, but also that the lesser motions themselves cannot be detected on account of the minuteness of their particles.* So basically, Newton's *sole* justification was his appeal to Nature's consonance: "whatever reasoning holds for greater motions, should hold for lesser ones as well". As we shall shortly see, Newton began to see the difficulty with such "transductive" arguments. Next, Newton gave several illustrations of such short-range attractive forces. He listed several chemical reactions during the course of which we can observe that the particles involved attract each other, i.e. approach one another, and pointed to the activity of cohesive forces.[89] Subsequently, he gave several illustrations of short-range repellent forces (for instance, the force by which the particles of oil repel the particles of water when mixed together).[90] Newton merely provided these examples in order to render the existence of short-range attractive and repellent forces more *plausible* and to, at least, justify further research on these matters. They certainly did not have a demonstrative nature. Newton freely admitted that he had not demonstrated that such non-gravitational forces are *verae causae*:

> I have briefly set these matters out, not in order to make a rash assertion that there are attractive and repulsive forces in bodies, but so that I can give opportunity to imagine further experiments by which it can be ascertained more certainly whether or not they exist. For if it shall be settled that they are true [forces] [This refers to (a) of the aforementioned issues of investigation.] it will remain for us to investigate their causes and

> properties diligently, as being the true principles from which, according to geometrical reasoning, all *the more secret motions of the least particles* are no less brought into being than are the motions of the greater bodies which we saw in the foregoing [books] derived from the laws of gravity [tanquam vera principia a quibus omnes particularum minimarum secretiores motus secundum rationes Geometricas non minus oriantur quam motus majorum corporum ex legibus Gravitatis in praecedentibus derivari vidimus].[91]

As it stood, Newton had not quite succeeded in deriving from mechanical principles by geometrical reasoning the lesser motions. In an additional paragraph, he wrote:

> I am far from affirming that my views are correct, and I acknowledge their great imperfection, nevertheless they are simple and easy to conceive, and of the same kind as the natural philosophy of the cosmic system which depends on the attractive forces of greater bodies.[92]

Now we will make a jump in time and turn to three experiments Newton intended to include in the General Scholium (see especially the A-version) concerning the electrical force (vis electrica) by which the particles of bodies are variously moved.[93] From 1707 onwards Newton was enormously fascinated by electricity as a direct consequence of a series of electrostatic experiments which were performed by Francis Hauksbee (1670-1713) at *The Royal Society*.[94] Initially Newton planned to add "about a quarter of a Sheet" on the attraction of the small particles of bodies to the General Scholium, but replaced it by the paragraph on "a certain subtle, electric spirit".[95] Ultimately these experiments turned out unsatisfactory to Newton, since in the General Scholium he did not mention them and he only declared that:

> But these things cannot be explained in a few words; furthermore, there is not a sufficient number of experiments to determine and demonstrate accurately the laws governing the actions of this spirit.[96]

By "this spirit" Newton most certainly referred to "the elastic and electric spirit".[97] In the first experiment Newton observed that when two contiguously placed pieces of glass were immersed in still water "the water [by the attraction of the glass] ascends between the pieces of glass above the surface of the water, and the height of ascent will be inversely as the distances between the glasses"[98]. He also added that the experiment "succeeds in the Boylian vacuum and so does not depend on the weight of the incumbent atmosphere"[99]. A variant of this experiment consisted in placing a drop of orange oil between two plates of glass (the first plate was placed horizontally and, at one end, met the second plate; the second plate was kept inclined and touched the drop of orange oil which lay at the other end of the first plate). As soon as the second plate touched the drop of orange oil, "the drop began to move towards the meeting-point of the glasses"[100]. This also succeeds *in vacuo*. Therefore: "the origin of this motion lies in the attraction of the glasses"[101]. Because of Newton's usage of screening-off procedures, these experimental set-ups were more sophisticated than those from the suppressed *Preface* and *Conclusion* to the first edition of the *Principia*, and, correspondingly, they added more substance to Newton's claims on these short-range attractive forces. The fact that these experiments also occurred *in vacuo* guaranteed that other forces (e.g. the pressure of the atmosphere, which was Newton's earlier explanation of the rising of water between glass plates[102]) can no longer be adduced as the causes of the phenomena under observation. But the sophistication was by no means limited to Newton's reliance on screening-off procedures: Newton also tried to quantify such short-range attractive forces. In a third experiment he described how, when the meeting point of the plates was raised so that the lower glass is now inclined to the horizon, the drop rose more slowly than previously and finally came to rest. In such a state of equilibrium, the weight is equal to the attraction of the glass:

> Thus from the inclination of the lower glass the weight of the drop is given, and from the weight of the drop the attraction of the glass is given. The inclinations of the lower glass by which the drop was maintained in equilibrium, and the distances of the drop from the meeting-point of the glasses, are shown in the following table [not given].[103]

In an ingenious way Newton tried to measure the short-range accelerative force of the glass by studying the weight in equilibrium of the drop at various inclinations. The missing table can be found on another draft of the General Scholium [*De vi electrica* (CUL Add. Ms. 3970: ff. 602-604)].[104] Since the experiments are described in more detail[105], Newton's writing is relatively neat throughout the manuscript[106], and the implications of the experiments are now discussed in a more straightforward manner, this draft is most likely written after the composition of the A-version to the General Scholium. As we have seen, in the A-version Newton had succeeded in providing more sophisticated proof for the existence of the "electrical" force. Correspondingly, his 1687 agnosticism about the existence of such force disappeared and Newton's tone became more determined in *De vi electrica*: "It is *certain from phenomena* that electric and magnetic attractions also exist."[107]. By these experiments, Newton noted, "it is *fully enough clear* that glass at small distances always abounds in electric force"[108]. However, the data Newton obtained when comparing the varying inclinations of the plate and the distances, from the meeting point of the plates to the place where the drop of orange oil is in equilibrium, did not suffice to yield an accurate determination of the law governing such attraction. The reader can understand Newton's dissatisfaction by comparing the values obtained when multiplying the inclinations (which stood as a measure for the attractive force of the glass) with the square of the corresponding distance. Newton could therefore only provisionally conclude that this force is "very nearly inversely in the ratio of the square of the distance"[109]. However, the existence of such forces could no longer be disputed.[110] The second half of this draft is devoted to showing how this "electric spirit" might also account for optical phenomena (refraction, reflection and inflexion), the state of aggregation of bodies, and, finally, fermentation and digestion.[111]

How are we to understand Newton's dissatisfaction with these observations and experiments related to the non-gravitational forces in nature? One might simply respond to this question by stating that the empirical data Newton required was not at hand. While this is certainly the case, there is a more fundamental reason to it. I shall commence by making some points on Newton's optics where he ran into similar difficulties as with his electrical spirit.[112] In his monumental study of Newton's optics[113], Alan E. Shapiro concludes that Newton's method of transduction was not up to the task of treating the colours of natural bodies.[114] Shapiro points out that Newton's failure in optics was due to the failure of the method of transduction *within* the domain of optics. Transduction refers to the method of making of inferences about the unobservable, *microscopic components* of bodies from the observed laws and properties of *macroscopic bodies*.[115] In such an inference, we apply the observed macroscopic properties of bodies to their microscopic constituents. Without transduction, it would be impossible, according to Newton's own words, to derive "the qualities of imperceptible bodies from the qualities of perceptible ones".[116] For instance, when arguing that opacity is produced by the parts of bodies, Newton used macroscopic examples.[117] Similarly, in the early 1670s, Newton assumed that coloured bodies, consisting of absorbing primordial particles and pores, are produced by the highest order corpuscles in the same way as a fragment of a thin film.[118] Again, Newton illustrated his theory with a macroscopic example. This seems to suggest that in his early optical work Newton considered the transduction of macroscopic properties to their microscopic constituents as unproblematic. The vulnerability of transduction, however, lies in the following: justifying transduction for the properties of light and colour depends, as Shapiro puts it, on the composition or hierarchical arrangement of the corpuscles that compose bodies.[119] In fact, Newton began to see this weakness in the early 1690s (which converges with Newton's utterances from the manuscript material we have just considered).[120] This primordial methodological assumption was based on the simplicity or analogy of nature.[121]

We can further understand Newton's dissatisfaction with his optical work by contrasting it with Newton's contentment with his mechanical work. In the study of the celestial and terrestrial bodies, the make-up of the affected entities (= the effects) is known. We know that the effects which we want to explain are material bodies moving along certain trajectories. We know the make-up of what we want to explain (bodies *and* their constituents have the property of *mass*). In optics, by contrast, we do not know the make-up of optical phenomena such as prismatic dispersion, because this would already presuppose an optical theory. In optics transduction is problematic because it amounts to asserting the corporality of light. In this case, we would be introducing concocted hypotheses into our natural philosophy. The same holds *salva veritate* for the other forces causing "other local motions which on account of the minuteness of the moving particles cannot be detected, such as the motions of the moving particles in hot bodies, in fermenting bodies, in putrescent bodies, in growing bodies, in the organs of sensation and so forth."[122]. Newton disliked having to *postulate* a variety of unobservable motion and particles, without having rigidly deduced them from phenomena.

We shall further illustrate this by means of an example why the method of transduction was successful in mechanics. Let us see how Newton arrived at *universal* gravitation in Proposition 7, Book III. In the preceding propositions Newton had proved that all planets gravitate towards each other and that the gravity of each planet varies inversely as the square of the distance. It follows by proposition 69, Book I, that gravity towards all planets is proportional to their mass. Since all the parts of a planet A are heavy towards planet B, and since the gravity of each part 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 an equal reaction (by the third law of motion), it follows that planet B will gravitate in turn towards all the parts of A, and its gravity to any one part will be to its gravity toward the whole of the planet as the matter of that part to the matter of the whole.[123] Hence, the gravity towards the whole planet arises from and is compounded of the gravity of the individual parts (Corollary 1). From Corollary 3 to Proposition 74, Book I, it follows that the gravity toward each of the individual particles of a body is inversely as the squares of the distance of the places from those particles (Corollary 2). *In mechanics, transduction is unproblematic because the constituents of bodies share the same theoretically relevant property with the bodies they constitute: namely, mass (which is a measure of inertia).* Newton's awareness of the problems with transduction did not stop him to excogitate further experiments (*cf.* the A-version). However, since they were not accurate enough and did not agree with Newton's high methodological standards, he chose to suppress them in the final version of the General Scholium.

One final point may be added to that. Let us look at Newton's explanation of the planetary motions. Newton derived that a centripetal force is a necessary (Proposition 1, Book I) and sufficient (Proposition, 2 Book I) cause for Kepler's area law: Kepler's area law is valid *if and only if* there is an acting centripetal force. 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 states that, in commenting on Propositions 1-3, Book I, Newton had demonstrated by mathematics that a mathematically descriptive law of motion was equivalent to a set of *causal* conditions of forces and motions.[124] 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 *quam proxime* (by Proposition 2 (or 3), Book I); and from the observation that Kepler's third law holds *quam proxime* he infers that this force varies inversely as the square of the distance (by Corollary 6 to Proposition 4, Book I).[125] In Proposition 2, Book III (which concerns the primary planets), he similarly infers a centripetal force (tending towards the

Sun) from the observation that the second law holds *quam proxime* (by Proposition 2, Book I) and that it varies inversely as the square of the distance from the observation that the third law holds *quam proxime* for the primary planets (by (Corollary 6 to) Proposition 4, Book I). The conditional sentences in Book I function as "inference-tickets"[126] 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).[127] In other words, Newton was using the law of inertia as a criterion for whether forces were acting on a body (and thus as a criterion for accepting the existence of forces). *By contrast, in disciplines of natural philosophy where microscopic phenomena were dealt with, no such inference-tickets were at hand, because we cannot introduce a theoretically relevant property without introducing hypotheses on the make-up of the microscopic phenomena we intend to explain.* However, it is clear that, as manuscript evidence testifies, demonstrating these (other) non-gravitational forces experimentally, according to the highly developed mathematical methodology he had spelled out in the *Principia*, was one of Newton's paramount endeavours as a natural philosopher.

J.T. Desaguliers raised the issue whether the cohesion of two balls of lead does not prove "the Doctrine of Attraction, your late president Sir *Isaac Newton*; and that there is a universal Attraction between the Parts of Matter in Nature, though some at such small Distances as to escape our Observations[?]"[128]. Whatever the cause of these attractions is: "yet most learned Men, of several Nations, would rather charge such Manifest Qualities and Operations of Nature with the Nick-Name of occult Qualities, than give the Honour to the *great discoverer (who is no more)* of those manifest Qualities and Principles of Motions"[129].

Summary

In this survey we have in full detail mapped the scientific development of Newtonian physics, by focussing on the *Philosophical Transactions (of the Royal Society of London)* and portrayed the rise and fall of the accommodation of Newton's scientific work and his legacy.

The post-Newtonian research papers in the *Philosophical Transactions* added nothing fundamental to Newton's claims in *The Opticks* and the

Principia. In physical astronomy, several of Newton's claims were worked out: Desaguliers for instance tried to deduce the figure of the earth from Newton's theory. In mechanics, Edmund Halley took over Newton's equilibrium account of the tides, Brook Taylor analysed the centre of gravity, Edward Waring made further research on the decomposition of forces, David Gregory derived the catenary from Newton's method of fluxions, John Keill offered an analytical method for Kepler's second law and Desaguliers sought to provide experimental data that proved the adequacy of the central mechanical concepts in Newton's physics – he would do likewise for Newton's optical work. Francis Hauwksbee worked intensely on the small scale attractive and repellent forces which Newton was not able to treat successfully. The scientific work as can be found in these papers was not accompanied with theoretical innovation. Rather, they are testimony of a consequent programme of working out Newton's natural philosophy.

Acknowledgements

The author is indebted to the Research Foundation (Fonds voor Wetenschappelijk Onderzoek – FWO Vlaanderen) for funding the author's postdoctoral research project.

References

1. W. King, *The Transactioneer with some Philosophical Fancies: In two Dialogues*, London, 1700, p. 19.

2. On the Royal Society and its foundation numerous studies exist (in reverse chronological order): M. Hunter. Robert Boyle and the Early Royal Society: a Reciprocal Exchange in the Making of Baconian Science, *British Journal for the History of Science*, 40 (2007) 1-23; M. Crosland, Relationships between the Royal Society and the *Académie des Sciences* in the Late Eighteenth Century, *Notes and Records of the Royal Society of London*, 59 (2005) 25-34; M. Feingold, in *The Practice of Reform in Health, Medicine and Science, 1500-2000: Essays for Charles Webster*, eds. M. Pelling and S. Mandelbrote, Ashgate, Aldershot, 2005, pp. 167-184; P.F. da Costa, The Making of Extraordinary Facts: Authentication of Singularities of Nature at the Royal Society of London in the First Half of the Eighteenth Century, *Studies in History and Philosophy of Science*, 33 (2002) 265-288; P.F. da Costa, The culture of Curiosity at the Royal Society in the First Half of the Eighteenth Century, *Notes and Records of the Royal Society of London*, 52 (2002) 147-166; R.W. Home, The Royal Society and the Empire: The Colonial and Commonwealth Fellowship, part 1, 1731-1847, *Notes and Records of the Royal Society of London*, 56 (2002) 307-332; A. Johns, Miscellaneaous methods:

authors, societies and journals in early modern England, *British Journal of the History of Science*, 33 (2000) 159-186; G.S. Rousseau and D. Haycock, Voices calling for reform The Royal Society in the mid-Eighteenth Century – Martin Folks, John Hill, and William Stukeley, *History of Science*, 37 (1999) 377-406; A. Rusnock, Correspondence Networks and the Royal Society, *British Journal for the History of Science*, 32 (1999) 155-169; J. Gascoigne, The Royal Society and the Emergence of Science as an Instrument of State Policy, *British Journal for the History of Science*, 32 (1999) 171-184; D.P. Mill, The Usefulness of Natural Philosophy: the Royal Society and the Culture of Practical Utility in the Later Eighteenth Century, *British Journal for the History of Science*, 32 (1999) 185-201; C.T. Bond, *Beyond the Plain Style: Writing Science in The Philosophical Transactions, 1681-1751*, University of Notre Dame, PhD dissertation, 1998; R. Sorrenson, Towards a History of the Royal Society in the 18th Century, *Notes and Records of the Royal Society of London*, 50 (1996) 29-96; M. Feingold, *The Royal Society of London, 1660-1740: History in the Archives*, Bethseda, University Publications of America, 1992; M. Hunter, *Establishing the New Science: The Experience of the Early Royal Society*, Woodbridge/Suffolk/Wolfeboro, Boydell & Brewer, 1989; M. Hunter, Promoting the New Science – Oldenburg, Henry and the Early Royal Society, *History of Science*, 26 (1988) 165-188; A.M. Strumia, Recent Studies in the History of the Royal Society in the 17th Century, *Rivista Storica Italiana*, 98 (1986) 500-523; M. Blay, Notes on the Influence of Baconian Thought at the Royal Society – Scientific Practice and Discourse in the Study of Phenomena of Color, *Études Philosophiques*, 3 (1985) 359-373; J.L. Heilbron, *Physics at the Royal Society during Newton's presidency*, L.A., William Andrews Clark Memorial Library, University of California, 1983; R.H. Sands, Physicists, The Royal Society, and Freemasonry, *Michigan Quarterly Review*, 20 (1981) 194-209; P.B. Wood, Methodology and Apologetics – Sprat, Thomas History of the Royal Society, *British Journal for the History of Science*, 13 (1980) 1-26; P. Dear, *Totius in Verba* – Rhetoric and Authority in the Early-Royal-Society, *Isis*, 76 (1985) 145-161; K.T. Hoppen, Nature of Early-Royal-Society, *British Journal for the History of Science*, 9 (1976) 1-24; M.B. Hall, The Royal Society Role in the Diffusion of Information in the 17th Century, *Notes and Records of the Royal Society of London*, 29 (1975) 173-192; T. Sprat, *History of the Royal Society of London*, London, Royal Society, 1667.

3. Andrade, *The Birth and Early Days of the Philosophical Transactions*, p. 9.
4. H. Oldenburg, Preface, *Philosophical Transactions*, 1665-6, 1, p. ii.
5. H. Oldenburg, Preface, *Philosophical Transactions*, 6 (1671) 2087-2093, 2087-2088.
6. H. Oldenburg, Preface, p. 2088.
7. [H. Oldenburg], Preface, *Philosophical Transactions*, 17 (1683) 581-582.
8. E.N. da C. Andrade, The Birth and Early Days of the Philosophical Transactions, *Notes and Records of the Royal Society of London*, 21 (1965) 9-27. For further details, vide. C.A. Rivington, Early Printers to the Royal Society 1663-1708, *Notes and Records of the Royal Society of London*, 39 (1984) 1-27; C.A. Rivington, Addendum: Early

Printers to the Royal Society 1663-1708, *Notes and Records of the Royal Society of London*, 40 (1986) 219-220; B. Allen, J. Qin and F.W. Lancaster, Persuasive Communities: A Longitudinal Analysis of References in the Philosophical Transactions of the Royal Society, 1665-1990, *Social Studies of Science*, 24 (1994) 270-310; D. Atkinson, The Philosophical Transactions of the Royal Society of London, 1675-1975: A sociohistorical discourse analysis, *Language in Society*, 25 (1996) 333-371; C.T. Bond, Keeping up with the Latest Transactions: The literary critique of scientific writing in the Hans Sloane years, *Eighteenth-Century Life*, 22 (1998) 1-17.

9. A.G. Gross, J.E. Harmon and M. Reidy, *Communicating Science, The Scientific Article form the 17th Century to the Present*, Oxford, Oxford University Press, 2002. For further details, vide. C. Bazerman, *Shaping Knowledge, The Genre and Activity of the Experimental Article in Science*, Wisconsin, University of Wisconsin Press, 1988; D.A. Kronick, *"Devant le Deluge" and other Essays on Early Modern Scientific Communication*, Lanham/Oxford, The Scarecrow Press, 2004; Heilbron, *Physics at the Royal Society during Newton's presidency* (in this book a long-term study is provided but it is not sufficiently fine-tuned for the author's present task).

10. E.A. Gross, *Communicating Science*, pp. 31-49; see also A.G. Gross, J.E. Harmon, and Reidy, M., Argument and 17th-Century Science: A Rhetorical Analysis with Sociological Implications, *Social Studies of Science*, 30 (2000) 371-396.

11. D. Atkinson, The *Philosophical Transactions* of the Royal Society of London, 1675-1975: A sociohistorical discourse analysis, *Language in Society*, 25 (1996) 333-371, p. 339.

12. Not only in physics but also in other disciplines such as medicine, see e.g.: J. Keill, De Viribus Cordis, *Philosophical Transactions*, 30 (1717/1719) 995-1000.

13. E.A. Gross, *Communicating Science*, p. 69.

14. E.A. Gross, *Communicating Science*, p. 91.

15. Atkinson, The *Philosophical Transactions* of the Royal Society of London, p. 342.

16. E.A. Gross, *Communicating Science*, p. 138.

17. J. Arbuthnott, An Argument for Divine Providence, taken from the constant regularity observ'd in the Births of Both Sexes, *Philosophical Transactions*, 27 (1710-1712) 186-190, p. 189.

18. Payne, An Account of a Fork Put up the Anus, That Was Afterwards Drawn out Through the Buttock, *Philosophical Transactions*, 33 (1724-1725) 409.

19. Heilbron, *Physics at the Royal Society during Newton's presidency*, p. 20, cf. pp. 21-23.

20. Heilbron, *Physics at the Royal Society during Newton's presidency*, p. 52. See further: J. Wallis, and C. Wren, A Summary Account of the General Laws of Motion, *Philosophical Transactions*, 3 (1668) 864-868.

21. [A. Auzout], Monsieur Auzout's Speculations of the Changes, Likely to be Discovered in the Earth and Moon, by Their Respective Inhabitants, *Philosophical Transactions*, 1 (1665-6) 120-123.

22. [A. Auzout], The Motion of the Late Comet Praedicted, *Philosophical Transactions*, 1665-6, 1, pp. 3-8. see also [A. Auzout], The Motion of the Second Comet Predicted, by the Same Gentleman, Who Predicted That of the Former, *Philosophical Transactions*, 1 (1665/6) 36-40.

23. [Auzout], The Motion of the Late Comet Praedicted, p. 4. The author will not correct the spelling of passages or insert "sic" to quotes.

24. [Auzout], The Motion of the Second Comet Predicted, by the Same Gentleman, Who Predicted That of the Former, p. 40 [italics added by the author].

25. [J. Hevelius], Monsieur Hevelius's Calculation of the Late Solar Eclipse's Quantity, Duration, & c, *Philosophical Transactions*, 1 (1665/6) 369-371.

26. [J. Hevelius], An Account of Hevelius His Prodromus Cometicus, Together with Some Animadversions Made upon It by a French Philosopher, *Philosophical Transactions*, 1 (1665/6) 104-116.

27. [Hevelius], An Account of Hevelius ..., p. 106.

28. J. Stirling, Methodus Differentialis Newtoniana Illustrata, *Philosophical Transactions*, 30 (1717/1719) 1050-1070, 1050-1051 (in this paper no technical modifications were made to Newton's calculus).

29. J.T. Desaguliers, An Experiment to Illustrate What Has Been Said in the Philosophical Transactions, No. 386, 387, 388, concerning the Figure of the Earth, *Philosophical Transactions of the Royal Society of London*, 33 (1724-1725) 201-222. see also J.T. Desaguliers, A Dissertation concerning the Figure of the Earth. Part the Second, *Philosophical Transactions of the Royal Society of London*, 33 (1724-1725) 277-304, 297-298.

30. Desaguliers, An Experiment to Illustrate What Has Been Said ..., p. 222.

31. Herschel, W., Astronomical Observations on the Rotation of the Planets Round Their Axes, Made with a View to Determine Whether the Earth's Diurnal Motion is Perfectly Equable, *Philosophical Transactions of the Royal Society of London*, 71 (1781) 115-138. see also W. Herschel, On the Construction of the Heavens, *Philosophical Transactions of the Royal Society of London*, 75 (1785) 213-266.

32. E. Halley, A Discourse Concernimg [sic] GRAVITY, and Its Properties, wherein the Descent of Heavy Bodies, and the Motion of Projects is briefly but fully handled: Together with the Solution of a Problem of great Use in GUNNERY, *Philosophical Transactions of the Royal Society of London*, 16 (1686-1692) 3-21.

33. E. Halley, De numero Radicum in Aequationibus Solidis as Biquadraticis, sive tertiae as quartae potestatis earumq; limitibus, tractatulus, *Philosophical Transactions of the Royal Society of London*, 16 (1687-1692) 387-402, p. 388.

34. Halley, De numero Radicum in Aequationibus Solidis as Biquadraticis, p. 5.

35. Halley, De numero Radicum in Aequationibus Solidis as Biquadraticis, p. 6.

36. Halley, De numero Radicum in Aequationibus Solidis as Biquadraticis, p. 5.

37. Halley, De numero Radicum in Aequationibus Solidis as Biquadraticis, p. 6.

38. B. Taylor, Propositiones aliquot de Projectilium motu Parabolico, *Philosophical Transactions of the Royal Society of London*, 31 (1720-1721) 151-163. See also M. Folkes, The Motion of Projectiles near the Earth's Surface consider'd, independent of the Properties of the Conic Sections, *Philosophical Transactions of the Royal Society of London*, 15 (1748) 137-147.

39. Halley, A Discourse Concernimg [sic] GRAVITY ..., pp. 9-13.

40. E. Halley, De Ratione Temporis quo grave labitur per rectam data duo puncta conjugentem, ad Tempus brevissimum quo, vi gravitatis, transit ab horum uno ad alterum per arcum Cycyloidis, *Philosophical Transactions of the Royal Society of London*, 19 (1695-1697) 424-425. See also E. Halley, Propositio Generalis Arearum dimensionem exhibens in universo illo Curvarum Genere quae revolutione aequabili Circuli super Basin quamvis vel rectilineam vel Circularem describi possint, &C, *Philosophical Transactions of the Royal Society of London*, 19 (1695-1697) 125-128.

41. E. Halley, The true Theory of the Tides, extracted from that admired Treatise of Mr. Isaac Newton, Intitled, *Philosophiae Naturalis Principia Mathematica*; being a discourse presented with that Book to the late King James, *Philosophical Transactions of the Royal Society of London*, 19 (1695-1697) 445-457 (This paper provided an intuitive account of how universal gravitation explains the tides, the planetary motions and the figure of the earth.). See also E. Halley, An Exact Account of the Three Late Conjunctions of Saturn and Jupiter, (within the Space or Less than Seven Months according to Accurate Observations) viz. Octob. 14. 82, &c. Together with an Account of what Other Conjunctions of Them There Happened for More Than 100: Years Last; Beginning at the Year 1563: And a Table Computed Whereby to Make an Estimate of what Other Conjunctions Have Happened for the Time Past, or That Will Happen for the Time to Come, *Philosophical Transactions of the Royal Society of London*, 13 (1683) 244-258.

42. Halley, The true Theory of the Tides ..., p. 446.

43. Halley, The true Theory of the Tides ..., p. 445.

44. Halley, The true Theory of the Tides ..., p. 451.

45. Halley, The true Theory of the Tides ..., p. 457.

46. B. Taylor, De inventione Centri Oscillationis, *Philosophical Transactions of the Royal Society of London*, 18 (1713) 11-21.

47. E. Waring, On the Resolution of attractive Powers, *Philosophical Transactions of the Royal Society of London*, 79 (1789) 185-198.

48. D. Gregory, CATENARIA, *Philosophical Transactions of the Royal Society of London*, 19 (1695-1697) 637-652, p. 637.

49. Gregory, CATENARIA, p. 637.

50. [Anon.], De Maximis & Minimis Quae in Motibus Corporum Coelestium Occurrunt, *Philosophical Transactions of the Royal Society of London*, 30 (1717-1719) 952-954, p. 952.

51. J. Keill, Problematis Kepleriani, de inveniendo vero Motu Planetarum, areas tempore proportionales in Orbibus Ellepticis circa Focorum alternum describentium Solutio Newtoniana, *Philosophical Transactions of the Royal Society of London*, 28 (1713) 1-10, p. 3. See also: H. Pemberton, Kepler's Method of computing the Moon's Parallaxes in Solar Eclipses, demonstrated and extended to all Deagrees of the Moon's Latitude, as also to the assigned Diameter, together with a concise Application of this Form of Calculation to those Eclipses, *Philosophical Transactions of the Royal Society of London*, 61 (1771) 437-454.

52. Ordered chronologically: J.T. Desaguliers, An Account of an Experiment Made on Thursday the Last Day of June, 1720 before the R. Society, to Show by a New Proof, That Bodies of the Same Bulk Do Not Contain Equal Quantities of Matter, and Therefore That There is an Interspers'd Vacuum, *Philosophical Transactions of the Royal Society of London*, 31 (1721-1722) 234-239; J.T. Desaguliers, An Account of Some Experiments of Light and Colours, Formerly Made by Sir Isaac Newton, and Mention'd in His Opticks, Lately Repeated before the Royal Society, *Philosophical Transactions of the Royal Society of London*, 29 (1714-1716) 433-447; J.T. Desaguliers, An Account of Some Experiments of Light and Colours, Formerly Made by Sir Isaac Newton, and Mention'd in His Opticks, Lately Repeated before the Royal Society, *Philosophical Transactions of the Royal Society of London*, 29 (1714-1716) 433-447; J.T. Desaguliers, Plain and Easy Experiment to Confirm Sir Isaac Newton's Doctrine of the Different Refrangibility of the Rays of Light, *Philosophical Transactions of the Royal Society of London*, 29 (1714-1716) 448-452; J.T. Desaguliers, An Account of Some Experiments Made on the 27th Day of April, 1719 to Find How Much the Resistance of the Air Retards Falling Bodies, *Philosophical Transactions of the Royal Society of London*, 30 (1717-1718) 1071-1078; J.T. Desaguliers, Remarks on Some Attempts Made towards a Perpetual Motion, *Philosophical Transactions of the Royal Society of London*, 31 (1721-1722) 81-82; J.T. Desaguliers, An Account of Some Experiments Made to Prove, That the Force of Moving Bodies is Proportionable to Their Velocities: (Or Rather That the Momentum of Moving Bodies is to be Found by Multiplying the Masses into the Velocities) In Answer to Such Who Have Sometime Ago Affirm'd, That That Force is Proportionable to the Square of the Velocity, and to Those Who Still Defend the Same Opinion, *Philosophical Transactions of the Royal Society of London* 23 (1722-1723) 269-279; J.T. Desaguliers, Animadversions upon Some Experiments Relating to the Force of Moving Bodies; with Two New Experiments on the Same Subject, *Philosophical Transactions of the Royal Society of London*, 32 (1722-1723) 285-290; J.T. Desaguliers, An Experiment to Illustrate What Has Been

Said in the Philosophical Transactions, pp. 344-345; J.T. Desaguliers, A Dissertation concerning the Figure of the Earth. Part the Second, *Philosophical Transactions of the Royal Society of London*, 30 (1724-1725) 277-304; J.T. Desaguliers, Experiments Relating to the Resistance of Fluids, Made before the Royal Society on Thursday, March the 30th, 1721, *Philosophical Transactions of the Royal Society of London*, 31 (1720-1721) 142-144; J.T. Desaguliers, An Account of Some Experiments Made to Prove, That the Force of Moving Bodies is Proportionable to Their Velocities: (Or Rather That the Momentum of Moving Bodies is to be Found by Multiplying the Masses into the Velocities) In Answer to Such Who Have Sometime Ago Affirm'd, That That Force is Proportionable to the Square of the Velocity, and to Those Who Still Defend the Same Opinion, *Philosophical Transactions of the Royal Society of London*, 32 (1722-1723) 269-279; J.T. Desaguliers, A Dissertation concerning the Figure of the Earth, *Philosophical Transactions of the Royal Society of London*, 33 (1724-1725) 201-222; J.T. Desaguliers, The Dissertation concerning the Figure of the Earth Continued, *Philosophical Transactions of the Royal Society of London*, 33 (1724-1725) 239-255; J.T. Desaguliers, Some Experiments concerning the Cohesion of Lead, *Philosophical Transactions of the Royal Society of London*, 33 (1724-1725) 345-347; J.T. Desaguliers, A Proposition on the Balance, Not Taken Notice of by Mechanical Writers, Explain d and Confirm'd by an Experiment before the Royal Society, *Philosophical Transactions of the Royal Society of London*, 36 (1729-1730) 128-134; J.T. Desaguliers, An Experiment to Shew That the Friction of the Several Parts in a Compound Engine, May Be Reduced to Calculation; By Drawing Consequences from Some of the Experiments Shewn before the Royal Society Last Year, upon Simple Machines, in Various Circumstances, by Me. Now Exemplified by the Friction in a Combination of Pullies, *Philosophical Transactions of the Royal Society of London*, 37 (1731-1732) 292-293; J.T. Desaguliers, An Account of Two Experiments of the Friction of Pullies, *Philosophical Transactions of the Royal Society of London*, 37 (1731-1732) 394-396; J.T. Desaguliers, An Account of Some New Statical Experiments, *Philosophical Transactions of the Royal Society of London*, 40 (1737-1738) 62-68; J.T. Desaguliers, An Extract from the Journal Books of the Royal Society, concerning Magnets Having More Poles Than Two, *Philosophical Transactions of the Royal Society of London*, 40 (1737-1738) 62-68; J.T. Desaguliers, Some Thoughts and Experiments concerning Electricity, *Philosophical Transactions of the Royal Society of London*, 41 (1739-1741) 175-185; J.T. Desaguliers, Some Thoughts and Conjectures concerning the Cause of Elasticity, *Philosophical Transactions of the Royal Society of London*, 41 (1739-1741) 175-185; J.T. Desaguliers, Experiments Made before the Royal Society, Feb. 2. 1737-8, *Philosophical Transactions of the Royal Society of London*, 41 (1739-1741) 193-199; J.T. Desaguliers, An Account of Some Electrical Experiments Made before the Royal Society on Thursday the 16th of February 1737-8, *Philosophical Transactions of the Royal Society of London*, 41 (1739-1741) 200-208; J.T. Desaguliers, An Account of Some Electrical Experiments Made at His Royal Highness the Prince of Wales's House at Cliefden, on Tuesday the 15th of April 1738. Where the Electricity Was Conveyed 420 Feet in a Direct Line, *Philosophical*

Transactions of the Royal Society of London, 41 (1739-1741) 209-210; J.T. Desaguliers, Some Things concerning Electricity, *Philosophical Transactions of the Royal Society of London*, 41 (1739-1741) 634-637; J.T. Desaguliers, An Account of Some Electrical Experiments Made before the Royal Society, on Thursday the 22d of January 1740-1741, *Philosophical Transactions of the Royal Society of London*, 41 (1739-1741) 637-639; J.T. Desaguliers, Electrical Experiments Made before the Royal Society, on Thursday, March 15th 1740-1, *Philosophical Transactions of the Royal Society of London*, 41 (1739-1741) 639-640; J.T. Desaguliers, Some Further Observations concerning Electricity, *Philosophical Transactions of the Royal Society of London*, 42 (1742-1743) 383-384.

53. Desaguliers, An Account of Some Experiments Made to Prove, That the Force of Moving Bodies is Proportionable to Their Velocities ..., pp. 269-279.

54. Desaguliers, An Account of Some Experiments Made to Prove, That the Force of Moving Bodies is Proportionable to Their Velocities ..., pp. 271-272.

55. Desaguliers, Animadversions upon some Experiments relating to the Force of moving Bodies ..., pp. 285-290.

56. B. Robins, A Demonstration of the 11th Proposition of Sir Isaac Newton's Treatise of Quadratures, *Philosophical Transactions of the Royal Society of London*, 34 (1726-1727) 230-236.

57. C. Walmestley, Of the Irregularities in the Planetary Motions, Caused by the Mutual Attraction of the Planets, *Philosophical Transactions of the Royal Society of London*, 52 (1761-1762) 275-335. See also C. Walmestley, Of the Irregularities in the Motion of a Satellite Arising from the Spheroidical Figure of Its Primary Planet, *Philosophical Transactions of the Royal Society of London*, 50 (1757-1758) 809-835; J. Ivory, On the Theory of the Perturbation of the Planets, *Philosophical Transactions of the Royal Society of London*, 122 (1832) 195-228.

58. J. Landen, A new Theory of the Rotatory Motion of Bodies affected by Forces disturbing such Motion, *Philosophical Transactions of the Royal Society of London*, 67 (1777) 266-295.

59. J. Landen, Of the Rotatory Motion of a Body of any Form Whatever, Revolving, without Restraint, about any Axis Passing through Its Center of Gravity, *Philosophical Transactions of the Royal Society of London*, 75 (1785) 311-332 (the previous results are extended to the motion of bodies of whatever form). Also see: S. Vince, An investigation of the Principles of progressive and rotatory Motion, *Philosophical Transactions of the Royal Society of London*, 70 (1780) 546-577.

60. I. Newton, A Letter of Mr. Isaac Newton, Professor of the Mathematicks in the University of Cambridge; Containing His New Theory about Light and Colors: Sent by the Author to the Publisher from Cambridge, Febr. 6. 1671/72; In Order to be Communicated to the R. Society, *Philosophical Transactions*, 6 (1671) 3075-3087.

60. [Anon.], An Extract of a Letter Lately Written by an Ingenious Person from Paris, Containing Some Considerations upon Mr. Newtons Doctrine of Colors, as Also upon the Effects of the Different Refractions of the Rays in Telescopical Glasses, *Philosophical Transactions*, 8 (1673) 6086-6087. See also F. Linus, A Letter of Mr. Franc. Linus, Written to the Publisher from Liege the 25th of Febr. 1675. st.n. being a Reply to the Letter Printed in Numb. 110. by Way of Answer to a Former Letter of the Same Mr. Linus, Concerning Mr. Isaac Newton's Theory of Light and Colours, *Philosophical Transactions*, 10 (1675) 499-501; A. Lucas, A Letter from Liege concerning Mr. Newton's Experiment of the Coloured Spectrum; together with Some Exceptions against His Theory of Light and Colours, *Philosophical Transactions*, 11 (1676) 692-698. For Newton's replies see: I. Newton, Extracts of Two Letters, the One of Mr. Newton, Concerning the Number of Colors, and the Necessity of Mixing Them All for the Production of White, &c; the Other, of a Philosopher at Paris, by Way of Answer to the Former, *Philosophical Transactions*, 8 (1673) 6108-6112; I. Newton, Mr. Newtons Answer to the Foregoing Letter Further Explaining His Theory of Light and Colors, and Particularly That of Whiteness; together with His Continued Hopes of Perfecting Telescopes by Reflections Rather than Refractions, *Philosophical Transactions*, 8 (1673) 6087-6092; I. Newton, A Particular Answer of Mr. Isaak Newton to Mr. Linus his Letter, Printed in Numb 121. p.499. about an Experiment Relating to the New Doctrine of Light and Colours: This Answer Sent from Cambridge in a Letter to the Publisher Febr. 29. 1675/6, *Philosophical Transactions*, 11 (1676) 556-561; I. Newton, Mr. Newton's Answer to the Precedent Letter, Sent to the Publisher, *Philosophical Transactions*, 11 (1676) 698-705.

62. Newton, A Letter of Mr. Isaac Newton ..., p. 3079.

63. Newton, A Letter of Mr. Isaac Newton ..., p. 3081.

64. J.T. Desaguliers, A Plain and Easy Experiment to Confirm Sir Isaac Newton's Doctrine of the Different Refrangibility of the Rays of Light, *Philosophical Transactions*, 29 (1714/16) 448-452.

65. I. Newton, *The Opticks or A Treatise of Reflections, Refractions, Inflections and Colours of Light*, New York, Dover, 1979, p. 405.

66. Newton, *The Opticks*, pp. 55-56.

67. Desaguliers, An Account of Some Experiments of Light and Colours, Formerly Made by Sir Isaac Newton, and Mention'd in His Opticks, pp. 433-447.

68. Desaguliers, A Plain and Easy Experiment to Confirm Sir Isaac Newton's Doctrine of the Different Refrangibility of the Rays of Light, p. 448.

69. Desaguliers, A Plain and Easy Experiment to Confirm Sir Isaac Newton's Doctrine of the Different Refrangibility of the Rays of Light, p. 449.

70. S. Horsley, Difficulties in the Newtonian Theory of Light, considered and answered, *Philosophical Transactions of the Royal Society of London*, 60 (1770) 417-440.

71. J. Knox, On some phenomena of colours, exhibited by thin plates, *Philosophical Transactions of the Royal Society of London*, 105 (1815) 161-181.

72. T. Young, The Bakerian Lecture, Experiments and Calculations relative to physical Optics, *Philosophical Transactions of the Royal Society of London*, 94 (1804) 1-16, 1.

73. D. Brewster, On the laws which regulate the polarisation of light by reflection from transparent bodies, *Philosophical Transactions of the Royal Society of London*, 105 (1815) 125-158.

74. J. Herschel, On the action of crystallized bodies on homogeneous light and on the causes of the deviation from Newton's scale in the tints which many of them develop on exposure to a polarized ray, *Philosophical Transactions of the Royal Society of London*, 110 (1820) 45-98.

75. F. Hauksbee, An Account of some Experiments, touching the Electricity and Light producible on the Attrition of several Bodies, *Philosophical Transactions*, 26 (1708-1709) 87-92. See also F. Hauksbee, An Account of an Experiment, touching the Production of Light within a Globe Glass, whose inward Surface is lin'd with Sealing-Wax, upon the Attrition of its outside, *Philosophical Transactions*, 26 (1708-1709) 219-221; F. Hauksbee, An Account of Experiments touching the Direction of a Drop of Oil of Oranges, between two Glass Planes towards any side of them is nearest press'd together, *Philosophical Transactions*, 27 (1710-1712) 395-396; G. Wheler, Some Electrical Experiments, chiefly regarding the Repulsive Force of Electrical Bodies, *Philosophical Transactions of the Royal Society of London*, 41 (1739-1741) 98-111; W. Henley, and T. Ronayne, An Account of some new Experiments in Electricity, *Philosophical Transactions of the Royal Society of London*, 64 (1774) 389-431; J. Priestley, An Account of Rings consisting of all the Prismatic Colours, made by Electrical Explosions on the Surface of Pieces of Metal, *Philosophical Transactions of the Royal Society of London*, 58 (1768) 68-74; T. Cavallo, Of the Methods of manifesting the Presence, and ascertaining the Quality, of small Quantities on Natural or Artificial Electricity, *Philosophical Transactions of the Royal Society of London*, 78 (1788) 1-22; B. Wilson, Farther Experiments in Electricity, *Philosophical Transactions of the Royal Society of London*, 51 (1759-1760) 896-906.

76. R.W. Howe, in *Contemporary Newton Research*, ed. Zev Bechler, Studies in the History of Modern Science 9, Dordrecht/Boston/London, D. Reidel Publishing Company, 1982, pp. 197-213.

77. I. Newton, *De motu et sensatione animalium*, Cambridge University Library, Add. Ms. 3970: f. 236r; M. Mamiani, and E. Trucco, Newton E I Fenomeni della Vita, *Nuncius*, 9 (1991) 69-96, 78-79; W. Wallace, The vibrating nerve impulse in Newton, Willis and Gassendi: First steps in a mechanical theory of communication, *Brain and Cognition*, 51 (2003) 66-94, 68-74.

78. Hall, R.A, and Hall, M.B., *Unpublished Scientific Papers of Isaac Newton, A selection from the Portsmouth Collection in the University Library*, Cambridge: Cambridge University Press, 1978, p. 333, pp. 350-351, pp. 355-359; Mamiani and Trucco, Newton E I Fenomeni della Vita, pp. 69-96, pp. 78-87; I. Newton, *The Principia, Mathematical Principles of Natural Philosophy*, Translated by Bernard I. Cohen and Anne Whitman. Berkeley/Los Angeles/London, University of California Press, 1999, pp. 287-292, pp. 943-944; Newton, *The Opticks*, p. 376, pp. 396-403.

79. Hall and Hall, *Unpublished Scientific Papers*, p. 187.

80. Newton, *The Principia*, pp. 943-944.

81. S. Ducheyne and E. Weber, The Concept of Causation in Newton's Mechanical and Optical Work, *Logic and Logical Philosophy*, 16 (2007) 265-288.

82. Hall and Hall, *Unpublished Scientific Papers*, p. 303.

83. Hall and Hall, *Unpublished Scientific Papers*, p. 304.

84. Hall and Hall, *Unpublished Scientific Papers*, p. 306.

85. Newton, *The Principia*, pp. 794-795. See also Newton, *The Opticks*, p. 397; J.E. McGuire and Rattansi, P.M., Newton and the 'Pipes of Pan', *Notes and Records of the Royal Society of London*, 21 (1966) 108-143, p. 125.

86. Newton, *The Principia*, p. 411, pp. 588-589.

87. Hall and Hall, *Unpublished Scientific Papers*, p. 307.

88. Hall and Hall, *Unpublished Scientific Papers*, p. 333 (emphasis added), cf. p. 321.

89. Hall and Hall, *Unpublished Scientific Papers*, pp. 333-336, cf. pp. 321-323.

90. Hall and Hall, *Unpublished Scientific Papers*, pp. 336-340, cf. pp. 324-327.

91. Hall and Hall, *Unpublished Scientific Papers*, pp. 340-341 (emphasis added).

92. Hall and Hall, *Unpublished Scientific Papers*, p. 345.

93. R.S. Westfall, *Never at Rest*, Cambridge, Cambridge University Press, 1980, pp. 744-748.

94. Westfall, *Never at Rest*, pp. 684-686; B.J.T. Dobbs, *The Janus Faces of Genius, The role of alchemy in Newton's thought*, Cambridge: Cambridge University Press, 1991, p. 222; Newton, *The Principia*, p. 281.

95. Westfall, *Never at Rest*, pp. 745.

96. Newton, *The Principia*, p. 944.

97. A. Koyré, and I.B. Cohen, Newton's "Electric and Elastic Spirit", *Isis*, 51 (1960) 337.

98. Hall and Hall, *Unpublished Scientific Papers,* p. 354.

99. Hall and Hall, *Unpublished Scientific Papers,* p. 354.

100. Hall and Hall, *Unpublished Scientific Papers*, p. 345.
101. Hall and Hall, *Unpublished Scientific Papers*, p. 345.
102. Westfall, *Never at Rest*, p. 746.
103. Westfall, *Never at Rest*, p. 455.
104. Newton, *The Principia*, pp. 287-292, p. 289.
105. Newton, *The Principia*, pp. 288-290.
106. Newton, *The Principia*, p. 283.
107. Newton, *The Principia*, p. 287 (emphasis added).
108. Newton, *The Principia*, p. 289 (emphasis added).
109. Newton, *The Principia*, p. 289.
110. Mamiani and Trucco, Newton E I Fenomeni della Vita, p. 86.
111. Newton, *The Principia*, pp. 290-292.
112. Ducheyne, S., On Optical and Mechanical Models: Newton's Failure to Construct a Satisfactory Theory of the Phenomena of Light and Colour, *Logique et Analyse*, 194 (2006) 199-223.
113. Alan E. Shapiro, *Fits, Passions and Paroxysms, Physics Method, and Chemistry and Newton's Theory of Colored Bodies and Fits of Easy Reflection*, Cambridge, Cambridge University Press, 1993.
114. Shapiro, *Fits, Passions and Paroxysms*, p. 134.
115. Shapiro, *Fits, Passions and Paroxysms*, pp. 4-5.
116. Shapiro, *Fits, Passions and Paroxysms*, p. 45.
117. Shapiro, *Fits, Passions and Paroxysms*, p. 114.
118. Shapiro, *Fits, Passions and Paroxysms*, p. 113.
119. Shapiro, *Fits, Passions and Paroxysms*, p. 45.
120. Shapiro, *Fits, Passions and Paroxysms*, p. 46.
121. Shapiro, *Fits, Passions and Paroxysms*, p. 44.
122. Hall and Hall, *Unpublished Scientific Papers*, p. 333.
123. Newton, *The Principia*, p. 811.
124. I.B. Cohen, *The Newtonian Revolution, with illustrations of the transformation of scientific ideas*. Cambridge: Cambridge University Press, 1980, p. 63, p. 28, p. 37.
125. Newton, *The Principia*, p. 797.

126. G.E. Smith, in *The Cambridge Companion to Newton,* eds. I.B. Cohen and G.E. Smith, Cambridge, Cambridge University Press, 2002, pp. 138-173, p. 143. See also S. Ducheyne, Mathematical Models in Newton's Principia: A New View of the Newtonian Style, *International Studies in the Philosophy of Science*, 19 (2005) 1-19; S. Ducheyne, The Argument(s) for Universal Gravitation, *Foundations of Science,* 11 (2006) 419-447.

127. Newton, *The Principia*, p. 802.

128. Desaguliers, QUERIES, concerning the Cause of Cohesion of the Parts of Matter, pp. 39-43, p. 39.

129. Desaguliers, QUERIES, concerning the Cause of Cohesion of the Parts of Matter, p. 42.

Philosophical Transactions (1665-1678). Ã— Close Overlay. A title history is the publication history of a journal and includes a listing of the family of related journals. The most common relationship is to a previous and/or continuing title, where a journal continues publishing with a change to its official title. Other common relationships include a journal that is a supplement to another journal, a journal that is absorbed into another journal, a journal that splits into two or more new journals, or two or more journals that merge to form a new journal. For each of these related journals, th Scientific journals published by the Royal Society. 1800 books. Books to be categorised by country.