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NEWTON ON ELECTRICITY AND THE AETHER*

It is well known that Newton became convinced towards the end of his life that electricity played a vital role in the operations of nature. In the famous final paragraph of the *Scholium Generale* that he added to the second edition of the *Principia*, published in 1713, he wrote of "a certain most subtle spirit which pervades and lies hid in all gross bodies." It was this active spirit that gave rise, he supposed, to the electrical attractions and repulsions that manifested themselves at sensible distances from most bodies after they had been rubbed, as well as to the cohesion of particles when contiguous. In addition, he surmised, it was the agency responsible for the emission, reflection, refraction, inflection and heating effects of light; and by its vibrations in "the solid filaments of the nerves," it carried sensations to the brain, and commands of the will from the brain to the muscles in order to bring about bodily motion.[1]

In Andrew Motte's 1729 English translation of the *Principia*, the electrical character of this strange substance was emphasized by the substitution of the phrase "this electric and elastic spirit" for Newton's unadorned "this spirit" (*hic spiritus*) in the final sentence. Yet Motte was by no means misrepresenting Newton's views here: on the contrary, the phrase *spiritus electricus* appears in one of the draft versions of the *Scholium Generale,*[2] and Newton later wrote in the margin of his own annotated copy of the second edition of the *Principia*, after the word *Spiritus*, the words *electrici & elastici.*[3] Moreover, the electrical character of the subtle spirit was already clear in the original published version of the Scholium, from the role Newton attributed to it of bringing about the motions traditionally subsumed under the rubric "electricity".[4] Being electrical, it is clearly not to be equated with the spirit of God, as Koyré once suggested it might be. Instead, it must be located unambiguously among the ranks of second causes.[5]

Soon after the publication of the *Scholium Generale*, Newton's views concerning the subtle spirit underwent some changes. These are reflected in the eight additional Queries, numbered 17–24, that he included in the new edition of his *Opticks*, published in late 1717.[6] In certain respects, the "Æthereal Medium" that he described in these Queries was like the "subtle spirit" of the earlier *Scholium Generale*. It shared with the subtle spirit such properties as rarity, subtlety, activity and elasticity. Like the subtle spirit, it

Z. Bechler (ed.), Contemporary Newtonian Research, 191–213.

was held responsible for the reflection, refraction, inflection and heating effects of light, and for the functioning of the nervous system in transmitting sensations from the sensory organs to the brain, and commands of the will from the brain to the muscles. No longer, however, was it said to be chiefly confined, as the "subtle spirit" was, to be pores of "gross bodies." On the contrary, Newton suggested that this new medium was by its elastic force "expanded through all the Heavens" and was densest, he thought, in spaces altogether devoid of ordinary matter. It was therefore a true aether, something the earlier "subtle spirit", being more localised, was not. The difference is important, and tends to be reflected in Newton's terminology.[7]

Henry Guerlac has argued that Newton's reintroduction of a genuine, universally disseminated aether at this point was inspired by an experiment performed before the Royal Society of London in 1716 by Jean Théophile Desaguliers, at Newton's instigation.[8] This experiment, on the comparative rates of cooling of thermometers in air and in vacuo, was described by Newton in one of the new Queries (Q. 18) added to the *Opticks* a year later; and Guerlac has drawn attention to a letter written by Desaguliers to Sir Hans Sloane many years afterwards, in which it is said in so many words that the experiment was carried out at Newton's behest.

In the course of the "aether" Queries, Newton applied his new conception to the explanation of optical phenomena in particular. Most of those which he had previously accounted for in terms of the "subtle spirit" were now said to depend upon the aether, and so, too, were the mysterious "fits" of easy reflection and easy transmission of light that he had discovered long before, but had always tended previously to leave unexplained. These, he now suggested, had their origin in vibrations excited in the aether by rays of light falling on the surfaces of pellucid bodies.[9]

It is notorious that elsewhere in the new Queries, in Query 21, Newton offered an explanation of gravity in terms of density gradients within his aether.[10] Some scholars have taken a similar explanation, in terms of the "subtle spirit," to be implicit in the *Scholium Generale,*[11] but this is to count for nought Newton's unambiguous statement in the immediately preceding paragraph of the Scholium that he feigned no hypotheses concerning the cause of gravity.[12] Furthermore, earlier drafts of the Scholium reveal that Newton in fact maintained a clear distinction between gravity, on the one hand, and the various effects he listed among those which would find their explanation in terms of the "subtle spirit."[13] With the apparent exception of electricity (and we shall see that in Newton's mind even this was in fact no exception), the latter all depended upon short-range forces only; apart from electricity, they occurred in the immediate vicinity of bodies, precisely where Newton said the "subtle spirit" was to be found. Newton rightly regarded gravity as being in a quite different category. If it was to be explained mechanically, a mechanical agent was required that extended, as the "subtle spirit" did not, over the entire space between widely separated material bodies. In other words, only when he replaced the "subtle spirit" by a universally disseminated medium did such an explanation become a possibility so far as Newton was concerned. And even after this, so Desaguliers tells us, Newton remained hesitant about identifying the "Medium acting upon light" with whatever it was that caused bodies to gravitate towards one another.[14]

The replacement of the "subtle spirit" of the *Scholium Generale* by the universal aether of the late Queries in the *Opticks* was attended by other, less striking changes in the explanatory role attributed to it by Newton. In particular, several of the phenomena that were said in 1713 to be explicable in terms of the "subtle spirit", namely cohesion, electrical attraction and repulsion, and the emission of light from luminous bodies, were not mentioned in 1717 among those brought about by aetherial action.

All these omissions were surely deliberate. Cohesion and the emission of light were, in Newton's general scheme of things, precisely the phenomena that depended upon the most intense and most short-range forces of all, one attractive, the other repulsive. Among the universal or quasi-universal forces of matter, these differed most from gravity in their mode of operation, and were therefore the least likely to be brought about by the same causal principle.

The omission of electricity was certainly intentional, as we learn from a passage in one of the newly inserted Queries, Query 22. Here, Newton confronts the question of how the motions of the heavenly bodies can continue undisturbed in an all-pervading medium such as the aether he is here invoking. His solution is to suppose that his aether is both extremely rare and extremely elastic; and to give this suggestion at least a modicum of plausibility, he cites instances already "known" in which matter retains its activity when reduced to a very low density. What is significant for us here is that one of his examples is the subtle matter which, he assumes, gives rise to electrical motions. "If any one would ask how a Medium can be so rare," he says, "let him . . . tell me, how an electrick Body can by Friction emit an Exhalation so rare and subtile, and yet so potent, as by its Emission to cause no sensible Diminution of the weight of the electrick Body, and to be expanded through a Sphere, whose Diameter is above two Feet, and yet to be able to agitate and carry up Leaf Copper, or Leaf Gold, at the distance of above a Foot from the electrick Body?"[15] There is no suggestion here that the aether and this electrical "exhalation" are one and the same thing. On the contrary, the electrical exhalation is taken for granted as something different, whose nature is well known and understood, and whose properties provide a useful analogy to buttress Newton's account of the aether. Unlike the "subtle spirit" of the *Scholium Generale*, the aether of the *Opticks* Queries is not an electrical spirit. By 1717, Newton's flirtation with the notion that electricity was a universal causative agency in the micro-realm was apparently at an end.

Or was it? It is plain from the passage just quoted that Newton's belief that electrical motions were brought about by *a* subtle spirit emitted by electric bodies was in no whit diminished. Furthermore, it was well known in his day that many if not all bodies could be rendered electrical by friction. All these bodies, at least, must therefore contain some kind of subtle and active matter that could it appropriate circumstances be extruded from them. In addition, the question of what caused cohesion and the emission of light remained unanswered. It seems likely that Newton continued to hold that these effects were brought about by an electric spirit that pervaded the pores of all gross bodies. Even if he did not, however, he certainly continued to believe in the existence of the electric spirit itself, as will be made abundantly clear in what follows. Hence, the universally disseminated aether of the 1717 *Opticks* Queries ought not to be seen as a transmogrification of the more localised electric spirit of 1713. Rather, it was a *second* active medium introduced into the discussion at this point, to which certain of the functions previously ascribed to the electric spirit had been transferred, and to which various others had been attributed in addition.[16]

This interpretation, if correct, prompts an obvious question. If, in 1717, Newton really saw the electric spirit and the aether as two different kinds of active medium, why did he not make this clearer to readers of the new edition of *Opticks*? Certain unpublished drafts of proposed additions to the Queries suggest that he initially intended to do so. In the end, however, his habitual caution won out, and the relevant passages were suppressed.

At one point in the preparation of the new edition, Newton brought together on a single sheet a series of insertions he intended to introduce into the original set of Queries published in 1704. Included amongst these was the well known passage, destined for Query 8, describing some of Francis Hauksbee's striking experiments with electrified glass globes. Almost all the proposed insertions were in due course included without further amendment in the new printing. The following, however, which Newton at first intended to insert as a new Query at "Pag. 134 lin 1" (that is, immediately after Query 8), was omitted:

Do not electric bodies by friction emit a subtile exhalation or spirit by which they perform their attractions? And is not this spirit of a very active nature & capable of emitting light by its agitations? And may not all bodies abound with such a spirit & shine by the agitations of this spirit within them when sufficiently heated? ffor if a long cylindrical piece of Ambar be rubbed nimbly it will shine in the dark & if when it is well rubbed the finger of a man be held neare it so as almost to touch it, the electric spirit will rush out of the Ambar with a soft crackling noise like that of green leaves of trees thrown into a fire, & in rushing out it will also push against the finger so as to be felt like the ends of hairs of a fine brush touching the finger. And the like happens in glass. If a long hollow tube of flint glass about an inch be rubbed nimbly with a paper held in the hand till the glass grows warm, it will in rubbing emit light & the face or any other tender part of the skin being held neare that part of the glass where it has been most rubbed, the electric spirit which is excited by the friction will rush out of the glass with a cracking noise & push against the skin so as to be felt, & in pushing emit light so as to make the skin shine like rotten wood or a glow worm. And if the glass was held neare pieces of leaf brass scattered upon a table the electric spirit w^ch^ issued out of the glass would stir them at the distance of 6, 8 or 10 inches or a foot, & put them into various brisk motions, making them sometimes leap towards the glass & stick to it, sometimes leap from it with great force, sometimes move towards it & from it several times with reciprocal motion, sometimes move in lines parall (*sic*!) to the tube, sometimes remain suspended in the air, & sometimes move in various curve lines. Which motions shew that this spirit is agitated in various manners like a wind. And if a broad plate of glass be placed between the tube & the pieces of brass, yet the Tube will attract them them (*sic*!), tho not so strongly as when the plate of glass is taken away. Which shews that the electrick spirit is so subtile as readily to pass through glass tho not so readily as through the Air. And whilst it pervades dense bodies so easily, why may it not be latent in them all in some measure or other, tho those only emitt it by friction in which it abounds most copiously? And since it easily emits light by agitation, why may it not emit light in all dense bodies heated red hot & thereby cause them to shine?[17]

No clearer statement could be desired of the rationale underlying Newton's linking of the emission of light with the activity of the electric spirit, nor of the grounds on which he concluded that this spirit was present in greater or lesser amounts in all gross matter. The experiments upon which Newton bases his arguments were due, like those with the glass globe, to Hauksbee, and date from the period 1706–1709. So far as its contents are concerned, therefore, the new Query could have been drafted at any time between about 1710 and late 1717. Yet the fact that the other passages on this page had reached their final form by the time the page was written out suggests that the whole was of relatively late composition, and perhaps even post-dated Newton's revived interest in a universal aether as an explanatory mechanism. More conclusive is the fact that Newton subsequently re-numbered his draft Query as "Qu. 18B." Since a Query of this kind would have been quite out of place between Queries 18 and 19 of the 1706 Latin *Optice* (that is, between Queries 26 and 27 in the 1717 English version), it must be that Newton intended it to go between the new Queries 18 and 19 of 1717, that is, between two of the early "aether" Queries in that edition. In other words, the re-numbering must have been done *after* the aether Queries themselves were drafted.

The extra Query would, in fact, have fitted quite logically at this point. It is precisely in Query 18 that Newton described Desaguliers' thermometer experiment and argued on that basis for the existence of a subtle medium, or aether, "expanded through all the Heavens."[18] There is not the slightest hint in the proposed Query 18B that the electric spirit discussed there was connected in any way with this universally disseminated agent. Rather, the new Query would have served immediately to introduce Newton's second subtle medium, an electric spirit that was also responsible for the emission of light from bodies under a variety of circumstances. In other words, it would have made plain his belief that there were in fact two different subtle media at work in the world.

For some reason, however, Newton was still not satisfied, and on the second of the pages into which the sheet was divided, he tried again, this time numbering it "Qu 24" and placing it after the last of the "aether" Queries and before the first of the re-numbered Queries from the Latin *Optice* (Query 22 of the eventual printed version was not included at this stage, so that the final "aether" Query was numbered 23, not 24):

Qu 24. Do not electric bodies by friction emit a subtile exhalation or spirit by w^{ch} they perform their attractions? And is not this Spirit – – – & thereby cause them to shine. Qu: 25 Are there not other original properties of light . . .[19]

Another attempt, which Newton numbered "Qu. 23", is recorded after this on the same page. It concentrates upon the detailed mechanism underlying electrical attraction and repulsion, and was presumably intended by Newton to preface his discussion in the proposed "Qu 24" of the involvement of electricity in the production of light. It includes an explicit suggestion that the electric spirit may be but one of several "subtle invisible Mediums which may have considerable effects in the Phaenomena of nature":

Qu. 23. Is not electrical attraction and repuls; performed by an exhalation w^{ch} is raised out of the electrick body by friction & expanded to great distances & variously agitated like a turbulent wind, & w^{ch} carrys light bodies along with it & agitates them in various manners according to its own motions, making them go sometimes towards the electric body, sometimes from it & sometimes move with various other motions? And when this spirit looses its turbulent motions & begins to be recondensed & by condensation to return into the electric body doth it not carry light bodies along with it towards the Electrick body & cause them to stick to it without further motion till they drop off? And is not this exhalation much more subtile than common Air or Vapour? For electric bodies attract straws & such light substances through a plate of glass interposed, tho not so vigorously. And may there not be other Exhalations & subtile invisible Mediums which may have considerable effects in the Phaenomena of nature?

And the same things have been found by rubbing a long & large cylinder of glass or Ambar with a paper held in ones hand, & continuing the friction till the glass grew warm.[20]

That electricity continued to be linked, so far as Newton was concerned, with the general phenomenon of cohesion is suggested by his choosing to append at this point a somewhat modified opening sentence for Query 31:

Qu. 31. May not the mutual attraction of the small parts of bodies be sufficiently strong to make them cohere & compose very hard bodies.

In the end, he did not use this, but he did add to the final sentence of the first paragraph of the same Query a remark that has since puzzled many an historian: "and perhaps electrical Attraction may reach to such small distances, even without being excited by Friction."[21] At this stage, he seems finally to have abandoned the idea of including an extended Query on the electrical spirit in the new edition of his book. In the end, all that remained was the brief allusion to an electric "exhalation" quoted earlier.

The significance of the document just described has been obscured by the presence in the same box of Newton's papers of a second set of draft Queries, also dealing with electrical matters, of which the first is again numbered 24. Quite understandably, there has been a tendency to assume that the two sets were connected at the drafting stage.[22] I believe, however, that they were not, and that the second set was in fact drafted somewhat earlier, probably at about the same time as the *Scholium Generale*. It reads as follows:

Quaest. 24. May not the forces by w^{ch} the small particles of bodies cohere & act upon one another at small distances for producing the above mentioned phænomena of nature, be electric? ffor altho Electric bodies do not act at a sensible distance unless their virtue be excited by friction, yet that virtue may not be generated by friction but only expanded, for the particles of all bodies may abound with an electric spirit w^{ch} reaches not to any sensible distance from the particles unless agitated by friction or by some other cause & rarefied by the agitation. And the friction may rarefy the spirit not of all the particles in the electric body but of those only w^{ch} are on the outside of it: so that the action of the particles of the body upon one another for cohering & producing the above-mentioned phænomena may be vastly greater then that of the whole electric body to attract at a sensible distance by friction. And if there be such an universal electric spirit in bodies, certainly it must very much influence the motions & actions of the particles of the bodies amongst one another, so that without considering it, philosophers will never be able to give an account of the Phænomena arising from those motions & actions. And so far as these phænomena may be performed by the spirit w^ch^ causes electric attraction it is unphilosophical to look for any other cause.

Quaest 25 Do not all bodies therefore abound w^th^ a very subtile active potent elastic spirit by w^ch^ light is emitted refracted & reflected, electric attractions & fugations are performed, & the small particles of bodies cohære when contiguous, agitate one another at small distances & regulate almost all their motions amongst them selves, ffor electric – – – uniting the thinking soul & unthinking body. This spirit may be also of great use in vegetation, wherein these things are to be considered, generation, nutrition & præparation of nourishment....

The Query then goes on to consider these aspects of living matter at some length.

In the passage quoted, Newton's dashes again indicate that he intended to take over *in toto* at this point a passage he had already written out elsewhere. The missing passage has been preserved as an un-numbered draft Query on the second half ot the sheet, and turns out to be quite extensive:

Quaest: Do not all bodies abound with a very subtil active vibrating spirit by w^ch^ light is emitted reflected & refracted, electric & magnetic attractions & fugations are performed, the small particles of bodies cohære when continguous, agitate one another at small distances & regulate almost all their motions amongst themselves as the great bodies of the Universe regulate theirs by the power of gravity? ffor electric bodies could not act at a distance without a spirit reaching to that distance. And by several experiments shewn by M^r^ Hawksby before y^e^ R. Society it appears that a cylindrical rod of glass or hard wax strongly rubbed emitts an electric spirit or vapour w^ch^ pushes against the hand or face so as to be felt, & upon application of the finger to y^e^ electric body crackles & flashes, & that the electric spirit reaches to y^e^ distances of half a foot or a foot from the glass or above & passes readily through the solid body of a plate or vessel of glass, the electric body attracting things beyond the glass; & that if a globe of glass be nimbly turned round upon an axis & in turning rub upon a man's hand to excite its electric virtue, the the (*sic*) hand if the glass be empty of air shines through the glass w^th^ a purple light, if some air be let into the glass, the whole cavity of y^e^ glass appears illuminated w^th^ flashes of a whiter light; if the Air be let in freely the glass emitts an electric vapour or spirit w^ch^ may be felt by the hand & w^ch^ in dashing upon the hand or upon white paper or a handkerchief at the distance of a quarter of an inch or half an inch from the glass or above, illuminates the hand or paper or handkerchief with a white light while the glass continues in motion, the spirit by striking upon those bodies being agitated so as to emit the light. & that if some threds of cotton or worsted yarn hanging by one end at a little distance from one another be attracted at the other end towards the glass, & a mans finger be advanced towards the attracted ends of the threds, the threds will recede from the finger, & this they will do as well when they are within the glass as when they are without it. There is therefore an electric spirit by w^{ch} bodies are in some cases attracted in others repelled & this spirit is so subtile as to pervade & pass through the solid body of glass very freely in both cases, & is capable of contraction & dilatation expanding it self to great distances from the electric body by friction. & thefore (*sic*) is elastic & susceptible of a vibrating motion like that of air whereby sounds are propagated. & this motion is exceeding quick so that the electric spirit can thereby emit light. And that w^{ch} emits light in the experiments above mentioned, may emitt it in all shining bodies whenever sufficiently agitated either by heat or by putrefaction. And the Medium w^{ch} emitts light may also be able to refract & reflect it as was noted above. This spirit may be also the Medium by whose vibrating agitations stirred up within dense bodies, the bodies receive heat & communicate it to contiguous bodies; the vibrations being propagated from one body into another where the bodies are contiguous, but reflected at the surface where they are not contiguous & by reflections kept within the hot body. The like vibrations may be excited in the bottom of the eye by light & propagated thence through the solid capillamenta of the optick nerves into the sensorium for causing vision & the like of other senses. The like vibrations may be also propagated from the brain through the solid fibres of the spinal marrow & its branches into y^e muscles for agitating & expanding the liquors therein & thereby contracting the muscles to cause the motions of animals. For as (*sic*) liquors are expanded by heat & by consequence by the vibrating agitations of this spirit. If the agitations be of short continuance they expand the liquors without heating them for want of time to do it. If lasting (as in running a race, or in supporting a burden without external motion of the body) they heat the body by degrees & at length excite sweat. This spirit therefore may be the medium of sense of animal motion & by consequence of uniting the thinking soul & unthinking body.[23]

As in the later, numbered version of the Query, Newton in this remarkable document then goes on to discuss the activity of living matter. His first paragraph is relevant here, because in it he explicitly invokes the electric spirit as the source of this activity:

The vegetable life may also consist in the power of this spirit supposing that this power in substances w^{ch} have a vegetable life is stronger then in others & reaches to a greater distance from the particles. ffor as the electric vertue is invigorated by friction so it may be by some other causes. And by being stronger in the particles of living substances then in others it may preserve them from corruption & act upon the nourishment to make it of like form & vertue w^{th} the living particles as a magnet turns iron to a magnet & fire turns its nourishment to fire & leaven turns past to leaven. ffor the living particles may propagate the vibrating motions of this spirit into into (*sic*) the contiguous particles of the nourishment & cause y^e spirit in those particles to vibrate & act after y^e same manner & by that action to modify the nourishment after the same manner with the living particles.[24]

There are two reasons for thinking that these passages are unconnected with those quoted previously, and were written somewhat earlier. First, their implications are rather different, because instead of being concerned with the electric spirit merely as the cause of electrical motions and the emission of light, as the others were, they assign to the spirit a very general explanatory function, much more typical of Newton's opinions at the time he composed the *Scholium Generale* than of his attitude a few years later when he wrote the "aether" Queries. More concretely, it emerges that these alternative Queries 24 and 25 were intended to go not after the final aether Query of 1717, Q. 23, but at a point indicated by Newton's note, "conjungi queant ut cohæerescant. p. 340. lin. 27", which turns out to be in the middle of what is now Q. 31, but which in the Latin *Optice* was Q. 23. They were thus drafted before ever Newton drew up the aether Queries and was led thereby to change his numbering scheme. The point where the new Queries were to be inserted comes at the end of Newton's long discussion of the various short-range forces at work in the world. He apparently intended to break off the existing Query at this point and argue for the electrical origin of these forces. Only then, presumably, would he have turned as he did in the original version to wider issues such as the tendency of the world gradually to run down, were not certain forces or active principles constantly at work in it.[25]

Professor Guerlac has described another bundle of papers from this fascinating collection, in which Newton wrote out a set of "Observations" to be included in a new edition of the *Opticks*. Several of these Observations deal with electricity. As in the passage quoted above, most of the experiments are Hauksbee's, including the production of light from a rubbed globe, the prickling sensation, crackling sound and light obtained when a finger is brought near a well rubbed piece of glass, and the motion of light bodies to and from an electrified tube; and on this occasion Newton also meant to include an account of an experiment he himself had reported to the Royal Society many years earlier.[26] He at first intended his "Observations" to come after the eleven Observations already set out in Book III of his *Opticks*, and he numbered them, accordingly, from XII to XV. Later, when Desaguliers' experiments convinced him anew of the existence of an aether, he decided to add emphasis to his discussion by setting it apart as a separate Part II of Book III. He included descriptions of Desaguliers' two leading experiments (the two-thermometer experiment and a variant of the old experiment in which a guinea and a feather were let fall together in a vacuum), called these Observations I and II, and renumbered the rest as Observations III to VI. Guerlac has on very plausible grounds dated the original drafting to late 1715 or 1716, while the amendments must have been made to it after Desaguliers devised his improved "guinea and feather" experiment in 1717.

A paper of Newton's headed "De vi electrica" was published a few years ago. A reference without further qualification to "Prop. XCIV, XCV & XCV (*sic*) Lib. I" indicates that, though now located among the manuscripts relating to the *Opticks*, this was destined initially for the *Principia*. It, too, discusses the "spirit hid in all bodies, by means of which light and bodies act upon each other mutually", that same spirit which is "the cause of electrical attraction and not only reflects, refracts and inflects light but also emits it," and whose vibrations in the nerves transmit sensations and the commands of the will. "Thanks to the same spirit the particles of bodies attract each other mutually at short distances, even without friction." Some further details are also provided, and these indicate – as do the links with the *Principia* and the wide range of phenomena ascribed to the subtle matter – that the document was drafted before Newton's reacceptance of a universal aether. "This spirit is not terminated in the external parts of bodies at a mathematical surface," we are told, "but becomes rarer gradually, and the more rare part of it spreads out from bodies on all sides to short distances and gradually comes to an end." Newton also suggests that we sense different colours as a result of vibrations of different "magnitude and number" being excited in the spirit "hidden within the capillaments of the optic nerve," and he spells out again the connections he envisages between the subtle spirit and the reflections, refractions, and alternate fits of easy reflection and easy transmission of light.[27]

To summarise: we may discern in the many papers dealing with electricity from this late period of Newton's life – papers in which the influence of Hauksbee's striking experiments is everywhere apparent – two different patterns of explanation. Newton found in Hauksbee's experiments proof that ordinary "gross" matter is everywhere pervaded by an active subtle spirit, responsible for the attraction of cohesion and, when excited by friction, for the attraction called electrical. When set vibrating, it brought about the emission of light. At first Newton believed this same spirit to be responsible also for the reflection, refraction, inflection, heating effects, and alternate fits of easy transmission and easy reflection of light, not to mention the operation of the nervous system in our bodies, and perhaps other functions of living matter as well. The *Scholium Generale* dates from this period, as do the draft "De vi electrica" and the extensive new Queries 24 and 25 meant to be inserted into Q. 23 of the Latin *Optice*. Soon afterwards, Newton drew up for inclusion in Book III of the *Opticks* the set of four additional Observations incorporating Hauksbee's leading results.

Following Desaguliers' success in November 1716 with the two-thermometer experiment, Newton took up again the idea of a universally disseminated aetherial medium. It was to this that he now attributed both the workings of the nervous system and the various optical phenomena previously ascribed to the electrical spirit. He also inclined to the view that this aether was the cause of gravity. Yet he did not altogether abandon the notion of a subtle electrical spirit pervading the pores of ordinary matter. On the contrary, he continued to attribute to the action of such a spirit not only specifically electrical effects but also the emission of light from luminous bodies and, probably, cohesion. A Query concerning the cause of gravity was drafted by July 1717,[28] and it must have been soon after this that the earlier set of Observations was recast to include an account of Desaguliers' work.[29] But then Newton had second thoughts, and decided to throw his new material into the form of Queries. The two-thermometer experiment went without difficulty into a new Query, Q. 18. The discussion of electricity was at first appended to Q. 8, but in the end only the section dealing with the production of light remained there. The passages in which Newton argued again for the existence of a subtle electric spirit were first relocated so as to come immediately after the account of the two-thermometer experiment, as Q. 18B, then moved again to the end of the "aether" Queries, and eventually omitted altogether. Only a hint of Newton's real views on this subject lasted into print, namely the passage in Q. 22 quoted above.[30]

Newton's intense interest throughout this period in the phenomena of electricity and the causes underlying them is manifest from the documents quoted above. Moreover, it seems he did not hesitate to make known to his colleagues at the Royal Society his hopes in this direction. In a French work from later in the century, he is quoted on the authority of Martin Folkes (F.R.S. 1714, and later President of the Society) as having urged the Fellows more than once to continue to investigate the subject with the utmost diligence: "Mes yeux s'éteignent, mon esprit est las de travailler, c'est à vous à faire les plus grands efforts pour ne pas laisser échapper un fil qui peut vous conduire."[31]

Yet the roots of Newton's fascination with electricity during this late period of his career have remained unclear. Zev Bechler has suggested that Newton seized on it as "the fundamental force of the micro-world" in very much a *post hoc* fashion, as the only one of the three forces known to act in the macro-world – gravity, magnetism and electricity – that fitted the technical requirements of his optical theory.[32] The documents we have quoted, however, tell a different story.

To begin with, they fully confirm Guerlac's suggestion that Hauksbee's experiments inspired Newton's renewed interest in the subject.[33] They show, in particular, that Newton found in Hauksbee's work direct experimental proof that a subtle electric spirit filled the pores of ordinary matter. In fact, most of the evidence he cites derives immediately from Hauksbee.[34] The electric spirit, Newton argues, can when excited by friction be detected directly by various of our senses. It can be felt pushing against our skin when we hold an electrified rod near our face or hand, and it can be both heard and seen (as a spark, we would say) when the point of a finger approaches the rod. If we use an electrified globe instead, the spirit can once again be felt "dashing upon the hand", and the hand and other bodies are illuminated by a white light, "the spirit by striking upon those bodies being agitated so as to emit the light." Besides these new and striking effects, however, Newton takes the age-old attraction of light objects towards an electrified body as proof enough in itself of the existence of the electric spirit. In a passage which squares extremely ill with a popularly held view of his general scientific approach, he baldly asserts that "electric bodies could not act at a distance without a spirit reaching to that distance."[35]

The remainder of Newton's argument follows very naturally, and not at all after the manner suggested by Bechler. Having already decided that agitating the electric spirit led to the emission of light, Newton found it a relatively small step to suppose that a similar cause lay behind the emission of light in other circumstances, that is, that "that w^ch^ emits light in the experiments above mentioned, may emitt it in all shining bodies whenever sufficiently agitated either by heat or by putrefaction." Since the spirit can be excited in most bodies by friction, and all bodies become luminous if heated sufficiently, the spirit must be universally present in matter. And from this apparently empirically well-founded position, the very general role that Newton ascribed to the electric spirit in bringing about the phenomena of the micro-world followed by a simple application of that much-abused philosophical principle, Ockham's razor. The relevant passage is worth quoting again in its entirely:

> And if there be such an universal electric spirit in bodies, certainly it must very much influence the motions & actions of the particles of the bodies amongst one another, so that without considering it, philosophers will never be able to give an account of the Phænomena arising from those motions & actions. And so far as these phænomena may be performed by the spirit w^ch^ causes electric attraction it is unphilosophical to look for any other cause.

Even Newton's subsequent change of heart on this last point is fully consistent with the position set out here. Desaguliers' experiment, without at all undermining the earlier parts of Newton's argument, nevertheless convinced Newton of the existence of a second subtle active medium. This made the application of Ockham's razor less straightforward, and meant that Newton had to choose between the two active spirits in assigning a cause to the various optical phenomena with which he had so long been concerned. But that is all.

In Q. 31, Newton cited electricity, along with gravity and magnetism, as examples of attractive forces already known to act in the world. "These Instances," he said,

> shew the Tenor and Course of Nature, and make it not improbable but that there may be more attractive Powers than these. For Nature is very consonant and conformable to herself .... The Attractions of Gravity, Magnetism, and Electricity, reach to very sensible distances, and so have been observed by vulgar Eyes, and there may be others which reach to so small distances as hitherto escape Observation; and perhaps electrical Attraction may reach to such small distances, even without being excited by Friction.[36]

Historians have generally assumed from this that for Newton the causes of magnetism and electricity were as mysterious and unknown as he generally took that of gravity to be. I have argued elsewhere, however, that in the case of magnetism this was not so, and that we ought to take literally Newton's caveat, "What I call Attraction may be perform'd by impulse, or by some other means unknown to me. I use that Word here to signify only in general any Force by which Bodies tend towards one another, whatsoever be the Cause."[37] Though sparse, all the available evidence suggests that, far from regarding magnetism as another unexplained force acting at a distance, Newton thought he knew the cause. The evidence indicates, in fact, that he attributed the power of the magnet to circulating streams of a peculiar subtle matter that passed axially through magnetized bodies and then returned through the external air before resuming its circulation once more. This theory was not original to Newton. It derived from the similar but more complicated scheme set out in Descartes' *Principia philosophiae* (1644), and was widely accepted by leading scientists in Newton's day. Similar conclusions ought to be reached, I believe, in the case of electricity. Here, too, Newton accepted a mechanistic explanation of the phenomena at hand. Here, too, the opinions he expounded were similar to those of his leading contemporaries, and resembled those set out in Descartes' *Principia philosophiae*. Electrical attraction and repulsion were not, for Newton, examples of unexplained forces acting at a distance.

In Descartes' day, the only generally recognized electrical phenomenon was the attraction that bodies such as amber, jet, sealing wax and glass exerted, when briskly rubbed, on nearby light objects. Descartes sought to reduce this, like all other natural phenomena, to motions and impacts among particles of matter. First, he suggested that the attraction might be brought about by a process analogous to what happens when a drop of viscous liquid hangs on the end of a rod, and the rod is shaken; part of the drop is seen to stretch out, and then to return promptly to the drop. Just so, Descartes envisaged the rubbing of a body as causing little branches composed of the smallest parts of the substances to spread out into the surrounding air: as these would, he said, remain joined together, they had to return immediately to the body, and in doing so could carry along any small objects that got entangled with them.[38]

Unfortunately, this account was incompatible with what Descartes had said earlier in his book concerning the nature of glass – yet glass, too, could be readily electrified by friction. To resolve the difficulty, Descartes invoked the finest of the three kinds of matter out of which he supposed the world to be constructed, his so-called "first element." When glass was rubbed, he said, thin strips composed of this fine and very mobile matter were forced out of the glass into the surrounding air. There, however, they found no pores fit to receive them, so they returned immediately to the glass, carrying with them any small bodies with which they became entangled. Nor, Descartes asserted, was this mode of attraction peculiar to glass: on the contrary, most cases of electrical attraction were brought about by this means, not by the mechanism he had first described.[39]

To modern eyes, Descartes' two mechanisms do not seem very different. In both, the electricity of bodies (that is, their ability to attract nearby light objects) is explained in terms of the "sweeping" action of some fine matter, initially ejected from the bodies in question as a result of their being rubbed, then returning to these bodies again. To seventeenth-century authors, however, the differences were important, and highlighted what remained for almost a century one of the chief unresolved questions in electrical theory. In the mechanism that Descartes preferred, the stuff involved was a universally disseminated subtle matter, or aether, whereas in the alternative model it was the matter of the rubbed body itself which brought about the effect.

Among Descartes' successors, opinions differed as to the relative merits of these two proposals. Orthodox Cartesians such as Rohault naturally tended to be guided by their master's opinions.[40] Boyle, on the other hand, confessed himself "very inclinable" to the view that ascribed the attractions to "the Emission of the finer parts of the attrahent," and in doing so he cited Digby, Browne and Gassendi as other proponents of it (in fact crediting

Digby with being its originator).[41] A generation later, Hauksbee, too, settled for this alternative. "The Effluvia which are provok'd from the Glass," he said, "seem to be, and are nothing else but part of the same Body exerted from it by rubbing." When, soon afterwards, he discovered that glass apparently allowed free passage to the effluvia emitted by rubbed sealing wax, he was most surprised, and could only suppose that "the Figure of the Parts of Glass and Sealing-Wax, are much alike, otherwise I cannot conceive how the Effluvia of one can penetrate and pass with such ease the Body of the other, and there to act as if it was one and the same with it."

In his early papers, Hauksbee tended, like Descartes, to regard the effluvia as solid threads of fine matter. At some time prior to the publication in 1709 of his *Physico-Mechanical Experiments on Various Subjects*, however, he changed his mind and came to see them instead as making up a subtle fluid. Boyle had also seen them in this light; but whereas Boyle had regarded them as "streams" which brought about the electrical attractions by condensing and returning to the glass, Hauksbee now ascribed the attractions to the inward motion of *air*, consequent upon the "Emission and Discharge of the Electrical Matter" from the electrified body. In Hauksbee's mature theory, in other words, there were two distinct streams of fluid matter in the vicinity of an electrified body, subtle matter from the rubbed body moving outwards and air moving inwards to take its place.[42]

Newton, in a brief discussion of electricity in his famous 1675 letter to the Royal Society setting out his "Hypothesis explaining the properties of light," made clear his allegiance at that stage of his career to a pattern of explanation similar to that accepted by his contemporaries. He first described an experiment in which small pieces of paper trapped in an air space beneath a piece of glass would "be attracted and move nimbly to & fro" with all manner of motions when the upper surface of the glass was rubbed with coarse cloth. To explain this, he, like Descartes but unlike English contemporaries such as Boyle, had recourse to a universal subtle matter, and concluded from the experiment that "there is something of an æthereall Nature condens'd in bodies." This, Newton supposed, was excited by the rubbing of the glass, and spread into the surrounding air. There it activated the little pieces of paper before recondensing into the glass again:

Now whence all these irregular motions should spring I cannot imagine, unless from some kind of subtill matter lyeing condens'd in the glass, & rarefied by rubbing as water is rarified into Vapour by heat, & in that rarefaction diffused through the Space round the glasse to a great distance, & made to move & circulate variously & accordingly to actuate the papers, till it returne into the glasse againe & be recondensed there. And as this condensed matter by rarefaction into an aethereall wind (for by its easy penetrating & circulating through Glass I esteeme it aethereall) may cause these odd motions, & by condensing againe may cause electricall attraction with its returning to the glass to succeed in the place of what is there continually recondensed; so may the gravitating attraction of the Earth be caused by the continuall condensation of some other such like aethereall Spirit . . .[43]

Newton's extensive discussions, quoted above, from a much later period of his life reveal that so far as the cause of electrical attraction was concerned, his view had changed hardly at all during the intervening period. Contrary to what has been suggested by the Halls,[44] Newton never envisaged the "electric spirit" as a Franklin-style fluid *collected* by friction on electrifiable bodies. On the contrary, he maintained with his contemporaries that electrification consisted in the *excitation* of matter already present in bodies, and he took it for granted that the various electrical motions were brought about in a wholly mechanical way by this agitated matter. As Newton put it, the exhalation raised out of bodies by friction "carrys light bodies along with it and agitates them in various manners according to its own motions."[45] Or again,

. . . the Agent or Spirit w^{ch} glass emits by friction, is agitated with various motions like a wind, carrying along with it little light bodies by means of w^{ch} you may know w^{ch} way it moves. And since for the most part it carries those bodies towards the glass & makes them stick to it, we may thence conclude that it is the spirit by which Electric bodies perform their attraction. The friction rarefies it & makes it expand it self into much more room then while it was in the glass. But it quickly begins to condense again & in condensing & shrinking into less room it returns into the glass & in returning carries along with it little light bodies & makes them stick to the glass untill it be all condensed & returned into the glass where it was before the friction.[46]

Newton frequently referred to the cause of the electrical motion as a "spirit". This does not mean, however, that he regarded it as some kind of immaterial agency, and electricity, therefore, as an irreducibly non-mechanical force.[47] In his 1675 letter to the Royal Society, Newton used the phrases "subtill matter" and "æthereall Spirit" interchangeably. In his later writings he sometimes calls the curious substance he is discussing an "exhalation", at other times a "vapour". Both terms imply a material nature, as Newton himself makes clear elsewhere, in a draft intended for the *Principia*:

Vapours and exhalations on account of their rarity lose almost all perceptible resistance, and in the common acceptance often lose even the name of bodies and are called spirits. And yet they can be called bodies in so far as they are the effluvia of bodies and have a resistance proportional to density.[48]

Likewise, he says the electric spirit "expands", and subsequently "condenses" and "shrinks" back into the body from whence it came. It can be "agitated", whereupon it "will rush out . . . with a soft crackling noise" and "push against the finger". On occasion Newton describes its "turbulent motions", which he compares to "a wind". He also says it is "susceptible of a vibrating motion like that of air". These are all terms appropriate to a material agency, but of very dubious application to an immaterial one. The most natural reading in every case – and the number of cases adds conviction here – is the one that sees Newton's ideas about electricity as firmly set in the same "Cartesian" mould as those of most of his contemporaries. To be sure, the electric spirit is "much more subtile than common Air or Vapour"; but the difference is one merely of degree, not kind.

There remains the difficult question of what Newton had in mind when in the 1717 edition of the *Opticks* he added to the sentence, "The Attractions of Gravity, Magnetism, and Electricity, reach to very sensible distances, and so have been observed by vulgar Eyes, and there may be others which reach to so small distances as hitherto escape Observation", the remark, "and perhaps electrical Attraction may reach to such small distances, even without being excited by Friction."[49] Hawes has argued that "Newton envisaged two distinct types of electric force", and maintains that in addition to the usual friction-induced attraction over appreciable distances that is effected by the electric spirit, for Newton "it is the small particles of matter which themselves possess an electric force, and by means of their inherent electric force they are able to act upon one another at small distances."[50] This is, in my opinion, seriously to mistake his meaning. Granted, Newton on several occasions mentions a number of experiments involving what we now call cohesion and surface tension, to show that a short-range attractive force that he describes as electrical acts between the particles of matter. This does not for a moment imply, however, that he conceived of this attraction as uncaused and inherent in the particles of matter themselves. On the contrary, in the final paragraph of the 1713 *Scholium Generale*, in the document "De vi electrica", and again in the draft "Quaest 25" quoted above, he expressly attributes the attraction, for reasons discussed already, to the action of the electric spirit.

What, then, is the distinction between "electrical attraction unexcited" and the ordinary friction-induced electrical force? Both, it appears, are brought about by the immediate action of the electric spirit, but whereas in the case of ordinary electrical attraction the spirit must first be made (by the friction) to spread across the intervening space until it reaches the bodies to be attracted, in the other the particles concerned are already within the range of activity of their associated electric spirit. In other words, in the case of the short-range force, the friction is simply unnecessary!

We have seen that in the case of ordinary electrical attraction, the electric spirit acts in a wholly mechanical way to push little light bodies towards an electrified object. Newton unfortunately nowhere tells us enough about the spirit's role in bringing about short-range forces for us to reach any definite conclusions about his view of its mode of action in this case. It is possible that, at this level, he envisaged the electric spirit acting by means of certain (unexplained) short-range forces between its particles and those of ordinary matter.[51] If what I have suggested above is correct, however, and short-range attractions are really no more than ordinary electrical attractions acting in a situation where no initial friction is necessary, then every analogy would suggest that Newton probably saw these forces, too, as caused mechanically by some kind of activity, perhaps vibrations,[52] in the electric spirit.

Such a conclusion cuts sharply across the tendency of recent Newtonian scholarship to stress the centrality of unexplained forces in Newton's mature philosophy of nature. It now appears that in several important cases – magnetism, electricity, and perhaps even short-range cohesive and chemical forces – Newton remained closer to the mechanistic modes of thought of his predecessors than has been appreciated. This is so especially in respect to the actual mechanisms he envisaged as causing ordinary magnetic and electrical attractions, but also in the general similarity between the function he alloted, in the passages quoted above, to his "very subtil active vibrating spirit," and that ascribed by Descartes to his "subtle matter" or "first element". In both cases, it seems, the substance in question provided the "go" for a wide range of hidden mechanisms on whose action the workings of nature depended.

There were differences, of course, between the Cartesian "first element" and Newton's "subtle spirit". Since Descartes' universe was a plenum, his subtle matter was necessarily dense. Also, its particles could not act either on each other or on particles of other matter except through contact. By contrast, Newton described the electric exhalation as "rare", which suggests that he conceived its particles to be widely separated. He also said that it was elastic, and if his discussion in the *Principia* of the elasticity of air is any guide, he would have taken this to mean that it was composed of particles mutually repelling each other at a distance. This, certainly, is how he proposed in 1717 to explain the elasticity of his newly re-introduced aether.[53]

These differences are important. So, too, is Newton's methodological emphasis on determining the laws of action of the various forces at work in the world. Unlike Descartes, he did not concern himself primarily with discovering the underlying causes of these forces. There is no inconsistency, however, in his nevertheless taking an interest in those underlying causes, or in his adherence in a number of cases to the general pattern of explanation provided by Descartes. Here, as elsewhere, we ought not to allow our recognition of Newton's extraordinary achievements in certain branches of science to blind us to the fact that in many respects he remained a child of his time.

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NOTES

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1 Isaac Newton, *Mathematical Principles of Natural Philosophy*, trans. Andrew Motte, rev. Florian Cajori (Berkeley/Los Angeles, 1934), p. 547.

2 A. R. and M. B. Hall (eds.), *Unpublished Scientific Papers of Isaac Newton* (Cambridge, 1962), pp. 357, 359. See also *idem*, 'Newton's Electric Spirit – Four Oddities', *Isis* **50** (1959), 473–476.

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

4 On the seventeenth-century meaning of the word "electricity", see N. H. de V. Heathcote, 'The Early Meaning of *Electricity*: Some *Pseudodoxia Epidemica*', *Annals of Science* **23** (1967), 261–275.

5 Koyré, *From the Closed World to the Infinite Universe* (Baltimore, 1957), p. 234. Cf. A. R. and M. B. Hall, 'Newton's Electric Spirit', pp. 475–476.

6 Isaac Newton, *Opticks, or a Treatise of the Reflections, Refractions, Inflections & Colours of Light* (New York, 1952: based on 4th ed., London, 1730), pp. 347–354. That the new edition was in print before the end of the year, and that it had already created quite a stir, is evident from the remark in a London newsletter dated 19 December 1717 that "Sir Isaac Newton has advanced something new in the last edition of his Optics, which has surprised his physical and theological disciples" (Historical Manuscripts Commission, *Report on the Manuscripts of His Grace the Duke of Portland*, V [Norwich, 1899], 550).

7 Sometimes, however, Newton was not so careful with his choice of words. For example, in an unpublished draft, discussed in more detail below, he referred to a "subtle Aether or Aetherial elastic spirit," an "aetherial spirit or spiritual effluvium" contained within gross bodies (University Library Cambridge, Add. MS. 3970, f. 626; quoted by Henry Guerlac, 'Newton's Optical Aether,' *Notes and Records of the Royal Society of London* **22** (1967), 45–57, p. 48.

8 Guerlac, *op. cit.*, pp. 48–52.

9 Newton, *Opticks*, p. 348. Both Guerlac, 'Newton's Optical Aether', *passim*, and R. S. Westfall, *Force in Newton's Physics* (London/New York, 1971), p. 395, have remarked upon Newton's emphasis on explaining optical phenomena in the "aether" Queries.

10 Newton, *Opticks*, pp. 350–352.
11 Cf. Joan L. Hawes, 'Newton and the "Electrical Attraction Unexcited"', *Annals of Science* 24 (1968), 121–130; p. 123.
12 Newton, *Mathematical Principles* . . . , p. 547. Cf. Koyré, *Newtonian Studies* (London, 1965), pp. 35–36, for the rendering of "fingo" as "feign" rather than "frame". J. L. Heilbron, *Electricity in the 17th and 18th Centuries* (Berkeley, 1979), p. 241, argues that Newton's "optical-gravitational aether" is actually incompatible with the earlier subtle spirit: "As the agent of cohesion, the electrical spirit should be present in bodies in proportion to their densities, while the optical-gravitational aether must stand rarer in denser bodies".
13 University Library Cambridge, Add. MS. 3965.12, ff. 350–365, quoted by Westfall, *Force in Newton's Physics*, pp. 392–393.
14 Desaguliers to Sir Hans Sloane, 4 March 1730/31, quoted by Guerlac, 'Newton's Optical Aether', p. 51.
15 Newton, *Opticks*, p. 353.
16 Newton's distinguishing between aether and electric spirits at this period has been noted by J. E. McGuire, 'Force, Active Principles, and Newton's Invisible Realm', *Ambix* **15** (1968), 154–208; pp. 179–81.
17 University Library Cambridge, Add. MS. 3970, f. 295. This and subsequent passages from Newton's papers are published by permission of the Syndics, Cambridge University Library.
18 Newton, *Opticks*, pp. 348–349.
19 University Library Cambridge, Add. MS. 3970, f. 293^{v}. Although bearing a folio number ahead of that given to the other half of the sheet, this was evidently drafted later, because the set of dashes in "Qu 24" as written out here clearly refers back to the longer version quoted previously.
20 *Ibid.*
21 Newton, *Opticks*, p. 376.
22 University Library Cambridge, Add. MS. 3970, f. 235. Cf. Westfall, *Force in Newton's Physics*, p. 416.
23 University Library Cambridge, Add. MS. 3970, ff. 241^{v} – 241^{r}. Joan L. Hawes has quoted extracts from this document in her article 'Newton's Two Electricities', *Annals of Science* 27 (1971), 95–103; pp. 96–97. (Folios 235 and 241 are the two halves of a single folded sheet.)
24 *Ibid.*, f. 241^{r}.
25 Cf. Newton, *Opticks* (1952), pp. 397ff.
26 University Library Cambridge, Add. MS. 3970, ff. 623–29, discussed in Guerlac, 'Newton's Optical Aether'. Cf. Newton to Henry Oldenburg, 7 December 1675; in H. W. Turnbull *et al.* (eds.), *The Correspondence of Isaac Newton* (Cambridge, 1959–77), I, 362–86; pp. 364–65.
27 University Library Cambridge, Add. MS. 3970, ff. 427–428^{v}; published in Newton, *Correspondence*, V, 362–65. In the accompanying English translation (pp. 365–68), Newton seems to attribute the "fits" to vibrations in the *air*. This, however, is not the sense of the Latin original.
28 Cf. Newton, *Opticks*, 'Advertisement II', p. [cxv].
29 Guerlac, noting that Desaguliers first reported his improved "guinea-and-feather" experiment to the Royal Society on 24 October 1717, has argued that "unless Newton

was privy to certain preliminary experiments", he could not have recast the set of Observations, and included an account of this experiment, until then. In fact, Desaguliers did perfect the experiment somewhat earlier, and doubtless promptly communicated the result to Newton. By September, Desaguliers had his apparatus working so well that he was able to demonstrate the experiment at Hampton Court before the King and the Princess of Wales (*Philosophical Transactions* **30** [1717], 717–20). Not until October, however, did the Royal Society reassemble after its customary summer recess, and so not until then could Desaguliers formally report his results to that body.

30 An unresolved puzzle, in the light of this analysis, is Newton's decision to leave the final paragraph of the *Scholium Generale* unaltered in the third (1726) edition of the *Principia*. It was presumably soon after the appearance of the previous (1713) edition that he thought about describing the subtle spirit more explicitly as "electric and elastic". Later, it seems he envisaged deleting the entire paragraph (Koyré and Cohen (eds.), *Isaac Newton's Philosophiae Naturalis Principia Mathematica: The Third Edition (1726) with Variant Readings* [Cambridge, 1972], II, 764). Does his eventual decision not to do so indicate that towards the end of his life he changed his mind yet again about the aether, and reverted to his previous ideas about a subtle spirit associated with bodies? But if so, why did he not then include the additional adjectives describing this spirit, as Motte did shortly afterwards in his English translation?

31 Comte de Tressan, *Essai sur le fluide électrique, considéré comme agent universel* (Paris, 1786), I, xliv–xlv. Though published very late in the century, this work was in fact written much earlier, in the 1740s (cf. Bibliothèque Nationale Paris, MS fr. 12280).

32 Bechler, 'Newton's Law of Forces which are Inversely as the Mass: a Suggested Interpretation of His Later Efforts to Normalise a Mechanistic Model of Optical Dispersion', *Centaurus* 18 (1973–74), 184–222; pp. 215–16.

33 Guerlac, 'Francis Hauksbee: expérimentateur au profit de Newton', *Archives internationales d'histoire des sciences* **16** (1963), 113–28; *idem*, 'Sir Isaac and the Ingenious Mr Hauksbee', pp. 228–53 in I. Bernard Cohen and René Taton (eds.), *Mélanges Alexandre Koyré: Tome I, L'aventure de la science* (Paris, 1964); *idem*, 'Newton's Optical Aether'.

34 Hauksbee's results were first published in numerous articles in the *Philosophical Transactions* in the years 1705–11, and were subsequently brought together in his *Physico-Mechanical Experiments on Various Subjects* (London, 1709; 2nd enlarged ed., 1719). I have discussed his work in my paper, 'Francis Hauksbee's Theory of Electricity', *Archive for History of Exact Sciences* 4 (1967), 203–17. Gad Freudenthal points out ('Early Electricity between Chemistry and Physics: The Simultaneous Itineraries of Francis Hauksbee, Samuel Wall, and Pierre Polinière', *Historical Studies in the Physical Sciences* **11** (1981), 203–229; p. 215) that Newton also drew upon the experiments of Dr Samuel Wall.

35 See above, p. 198.

36 Newton, *Opticks*, p. 376.

37 *Ibid.* Cf. R. W. Home, '"Newtonianism" and the Theory of the Magnet', *History of Science* **15** (1977), 252–66.

38 Descartes, *Principia philosophiae* (1644), in C. Adam and P. Tannery (eds.), *Oeuvres de Descartes* (Paris, 1897–1913), VIII, 311.

39 *Ibid.*, pp. 312–314.

40 Jacques Rohault, *A System of Natural Philosophy* (London, 1723; reprinted New York, 1969), II, 186–187.

[41] Boyle, *Experiments and Notes about the Mechanical Origine or Production of Electricity* (London, 1675: reprinted Oxford, 1927), pp. 3–6.
[42] R. W. Home, 'Francis Hauksbee's Theory of Electricity', *passim.*
[43] Newton, *Correspondence*, I, 365.
[44] A. R. and M. B. Hall (eds.), *Unpublished Scientific Papers of Isaac Newton*, p. 209.
[45] University Library Cambridge, Add. MS. 3970, f. 293^{v}.
[46] *Ibid.*, f. 628. Newton's failure to concern himself here with explaining electrostatic repulsion suggests that, like those of his predecessors who had noticed it, he regarded the effect as a mere mechanical rebounding and not a real phenomenon. Hauksbee thought otherwise, for reasons of which Newton must have been well aware.
[47] Cf. McGuire, 'Force, Active Principles, and Newton's Invisible Realm', p. 176, where Newton's assertion, "And so far as these phænomena may be performed by the spirit w^{ch} causes electric attraction it is unphilosophical to look for any other cause" (cf. p. 198 above) is taken to mean that " 'it is unphilosophical to look for any other cause' of electrical attraction." As indicated earlier, I, on the contrary, see the passage as an invocation of Ockham's razor with respect to the cause of "the motions & actions of the particles of the bodies amongst one another" more generally. I do not see it as an abandonment of the search for a mechanical explanation of electricity.
[48] University Library Cambridge, Add. MS. 3965.13, f. 437^{v}; quoted by McGuire, 'Body and Void in Newton's De Mundi Systemate: Some New Sources', *Archive for History of Exact Sciences* 3 (1966), 206–48, p. 219 (Latin original p. 245).
[49] Newton, *Opticks*, p. 376.
[50] Hawes, 'Newton and the "Electrical Attraction Unexcited" ', pp. 125–26; and *idem*, 'Newton's Two Electricities', *passim.*
[51] Heilbron, Note 12 above, p. 240.
[52] See above, p. 198. Another document tells us that the "agitation" of the spirit *softens* hard bodies and converts them into liquids (University Library Cambridge, Add. MS. 3970, f. 604). The same document adds chemical forces to the range of phenomena explained in terms of the electric spirit. Relevant passages are quoted, and an English translation provided, in McGuire, 'Force, Active Principles, and Newton's Invisible Realm', pp. 177–78. Since elsewhere in this document Newton attributes reflection, refraction and so on to the electric spirit, the whole presumably pre-dates his return to the idea of a genuine aether in late 1716.
[53] Cf. Newton, *Mathematical Principles . . .*, pp. 295–302, and *Opticks*, p. 352.