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RESEARCH ARTICLE

'Like nets or cobwebs': Kenelm Digby, Isaac Newton and the problem of rarefaction

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Abstract

This article aims to bring out the problematic nature of condensation and rarefaction for early modern natural philosophers by considering two historically significant attempts to deal with it, first by Sir Kenelm Digby in his *Treatise on Body* (1644), and subsequently by Isaac Newton, chiefly in manuscript works associated with the *Principia* (1687). It is argued that Digby tried to sidestep the problem of variation in density and rarity by making it a fundamental starting point for his physics. But he also brought out the difficulties of dealing with condensation and rarefaction within the mechanical philosophy, whether that philosophy was plenist or allowed for void space. The problems became exacerbated after experiments with the air-pump achieved extreme rarefactions. It is argued that these led Newton to first consider a retiform or net-like structure of matter, before adopting the radical innovation of supposing repelling forces operating at a distance between the particles of the rarefied bodies. Eventually, Newton came to believe that extreme rarity was inexplicable 'by any other means than a repulsive Power'.

Those physical changes which involve what we call condensation or compression on the one hand, and dilatation or rarefaction on the other, were always regarded as highly problematic until the advent of the kinetic theory of gases in the nineteenth and early twentieth centuries.[1] The linked concepts of condensation and rarefaction came to be seen as especially challenging during the development of the mechanical philosophies in the seventeenth century, as the previously dominant Aristotelian account of these phenomena finally came to be questioned. The difficulties were different for plenist philosophers (who believed that void space was impossible, and held the world to be completely full), and for atomists who allowed void space. In brief, compression in a plenum seemed to contradict the age-old assumption that two bodies could not be in the same place at the same time – if a body was compressed into half its volume, then half of it must then be occupying the same place as the other half. If a body was held to become less dense, or rarer, this seemed to imply that less matter was taking up the same space as more matter had previously done; this seemed at least counterintuitive, if not impossible. Atomists had an easy explanation for condensation – the atoms comprising a body were merely crowded closer together, filling up the empty spaces between the atoms. The

[1] See Stephen G. Brush, *The Kind of Motion We Call Heat: A History of the Kinetic Theory of Gases in the Nineteenth Century*, Amsterdam: North-Holland, 1976.

corresponding explanation of rarefaction, however, the spreading out of the atoms in space to leave greater voids between them, seemed to suggest that the atoms were capable of spacing themselves out. This in turn implied that the atoms could act upon one another at a distance, giving rise to what Aristotle had referred to as 'self-determined voids' between them – a state of affairs which was regarded as at least as untenable as two bodies occupying the same place at the same time.[2]

In spite of these long-standing and seemingly intractable difficulties for seventeenth-century thinkers, historians of science have paid remarkably little attention to them. It is not difficult to see why. The problems of condensation and rarefaction in the early modern period were closely associated with problems of vacuum, and ideas about the weight and elasticity, or spring, of the air. Both of these topics have attracted a great deal of attention from scholars, from Edward Grant's *Much Ado about Nothing*, to William Knowles Middleton's *History of the Barometer*, and Steven Shapin and Simon Schaffer's *Leviathan and the Air-Pump*.[3] In all of these, and numerous other works in the same areas, condensation and rarefaction necessarily make many incidental appearances, but they are seldom recognized as major problems in their own right, as the authors maintain their focus on the Torricellian vacuum, the origins of Boyle's law or whatever else might be their main concern.

Consider, for example, Charles Webster's 'The discovery of Boyle's law and the concept of the elasticity of the air in the seventeenth century'.[4] Although Webster frequently notes his subjects' talk of the spontaneous rarefaction of the air, or the air's 'force of dilatation', or 'the great powers of rarefaction and condensation of air', he does not stop to consider these beliefs, except in so far as they lead to Boyle's discovery of his famous law.[5] And yet, it should be easy to see that such talk of spontaneous powers in the air was highly contentious to the newly emerging mechanical philosophers. The aim of the mechanical philosophies, in all their different versions, was to reduce all explanations of natural phenomena to matter in motion, and to do away with supposed powers, faculties, occult qualities, vital principles and the like.[6] Consequently, condensation and especially rarefaction came to be seen as serious problems.

One historical case in which the problematic nature of condensation and rarefaction is all too obvious, that of Descartes, has also failed to lead to scholarly recognition of the wider and more general problem. Cartesian scholars, while recognizing the difficulties confronting Descartes's system (which will be discussed later), have tended to discuss it apologetically, defending Descartes's approach as acceptable within its own terms.[7]

[2] Aristotle, *Physics*, IV, Chapter 9, 216a 31. Action at a distance was held to be the supposed action of one body on another without the bodies making physical contact with one another. A magnet's action on a piece of iron is a prime example. Of course, this did not include cases where the movement of one body could be communicated to another by an intervening material medium. Hearing a distant explosion is not an example of action at a distance, because the air constitutes a material connection between the explosion and the ear. Similarly, a body that emanates material effluvia can affect another body, and this does not count as action at a distance, because the effluvia constitute a material connection. To count as action at a distance the action must be performed by some immaterial entity.

[3] Edward Grant, *Much Ado about Nothing: Theories of Space and Vacuum from the Middle Ages to the Scientific Revolution*, Cambridge: Cambridge University Press, 1981; William E.K. Middleton, *The History of the Barometer*, Baltimore: Johns Hopkins University Press, 1964; Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life*, 2nd edn, Princeton, NJ: Princeton University Press, 2011.

[4] Charles Webster, 'The discovery of Boyle's law and the concept of the elasticity of the air in the seventeenth century', *Archive for the History of the Exact Sciences* (1965) 2, pp. 441–502.

[5] Webster, op. cit. (4), pp. 451, 450, 448. See also note 66 below.

[6] For an introduction to the mechanical philosophies see, for example, Peter Dear, *Revolutionizing the Sciences: European Knowledge and Its Ambitions, 1500–1700*, Basingstoke: Palgrave, 2001, pp. 80–100.

[7] See, for example, M.L. Miles, 'Condensation and rarefaction in Descartes' analysis of matter', *Nature and System: Philosophical Studies of Natural and Artificial Systems* (1983) 5, pp. 169–80; Desmond M. Clarke, *Occult*

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Understandably, given their focus, these scholars have not been diverted into discussing the broader historical issues of condensation and rarefaction.

Fortunately, the neglect of the early modern problematic of condensation and rarefaction has recently shown signs of coming to an end. Silvia Manzo has shown, among other things, the role that was played by theories of motion in Girolamo Cardano's and Francis Bacon's attempts to explain rarefaction and condensation, and how these ideas were taken up by Francis Glisson and Matthew Hale in their own attempts to explain how these phenomena were possible.[8] Similarly, Xiaona Wang has included this problematic in her recent survey of how early modern thinkers dealt with occult qualities. After a brief summary of ancient and medieval views, Wang takes Bacon as her early modern starting point, and also includes Hale, taking in the work of early English atomists from Walter Warner to Walter Charleton, before moving on to Boyle and Newton. As well as noting the vitalistic elements in attempts to explain these phenomena, she also points out the increased urgency of the problem as the air-pump enabled Boyle to rarify air to such an extent that it took up over 500,000 times its previous volume.[9]

In this article, I want to extend this important work and bring into the discussion the attempt of Sir Kenelm Digby to maintain the Aristotelian account of condensation and rarefaction, while still developing a system of mechanical philosophy – indeed, the earliest system of mechanical philosophy written in English, in his *Treatise on Body* of 1644.[10] Digby's efforts are interesting in their own right, being representative of the seriousness of efforts to accommodate condensation and rarefaction in the new philosophies. But he also provides a highly insightful and enlightening critique of other contemporary attempts, both plenist and vacuist, to solve the problems associated with condensation and rarefaction. After a brief look at Boyle, who echoes and reinforces Digby's critique, I then turn to Isaac Newton's attempts to solve the problem of rarefaction, now made more urgent by Boyle's air-pump experiments.

Newton's efforts to deal with this issue of rarefaction not only reinforce the fundamental difficulties that the concept of rarefaction caused, but also throw new light on the development of his thinking, especially in the later part of his career, from the *Principia* (1687) to the *Optice* (1706). Moreover, his solution to the problem was to have far-reaching consequences for physics, until it was superseded by the kinetic theory of gases. I hope that this exposition of attempts to deal with the problem of how rarefaction is possible, added to those of Manzo and Wang, will serve to draw attention to condensation and rarefaction as a major problematic for early modern thinkers, who saw them, as Wang has rightly pointed out, as 'fundamental aspects of the natural world'.[11] These interrelated phenomena raised serious problems for those trying to develop a system of mechanical philosophy, and in the hands of Newton led to a philosophy of

Powers and Hypotheses: Cartesian Natural Philosophy under Louis XIV, Oxford: Clarendon Press, 1989, pp. 76–7; Dennis Des Chene, *Physiologia: Natural Philosophy in Late Aristotelian and Cartesian Thought*, Ithaca, NY: Cornell University Press, 1996, pp. 350–3; and Roger Ariew, *Descartes and the Late Scholastics*, Ithaca, NY: Cornell University Press, 1999, pp. 136–8.

[8] Silvia Manzo, 'From *attractio* and *impulsus* to "motion of liberty": rarefaction and condensation in Cardano, Francis Bacon, Glisson and Hale', in Cecilia Muratori and Gianni Paganini (eds.), *Early Modern Philosophers and the Renaissance Legacy*, Dordrecht: Springer, 2016, pp. 99–118.

[9] Xiaona Wang, *Handling 'Occult Qualities' in the Scientific Revolution: Disciplines and New Approaches to Natural Philosophy, from John Dee to Isaac Newton*, Leiden: Brill, 2023, pp. 151–69, 204–10, see p. 169 for the report of Boyle achieving a 500,000-fold increase of volume.

[10] Sir Kenelm Digby, *Two Treatises in the One of which, the Nature of Bodies; in the other, the Nature of Mans Soule; is looked into: In way of Discovery, of the Immortality of Reasonable Soules*, Paris: Gilles Blaizot, 1644.

[11] Wang, op. cit. (9), p. 153.

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interparticulate forces which, along with his theory of gravity, exposed the inadequacy of mechanical philosophies aimed at explaining everything in terms only of matter in motion.

Sir Kenelm Digby's *Treatise on Body* is a good place to start because Digby made condensation and rarefaction fundamental principles of his mechanical philosophy – the starting points from which all else followed. His efforts were sufficiently impressive that G.W. Leibniz, in a late work that was mostly critical of contemporary, or near contemporary, natural philosophers, 'Antibarbarus physicus', praised Digby not only for teaching 'that everything in corporeal nature should be explained mechanically', but more specifically for proposing 'an absolute condensation and rarefaction'.[12]

It is by no means immediately obvious what Leibniz might have meant by this latter comment, or why he might have regarded it as a praiseworthy feature of Digby's *Treatise on Body*.[13] It is certainly not intuitive to see a connection between a concept of 'absolute condensation and rarefaction' and purely mechanical explanations. A close reading of Digby's *Treatise on Body*, however, perhaps reveals what Leibniz might have meant, and makes it possible to reconstruct why he saw this as showing that Digby, at least in this regard, 'did not philosophize badly'.[14]

Leibniz's approval of Digby's treatment of condensation and rarefaction is significant because no consensus had ever been reached as to how these linked phenomena should be understood – neither in Digby's day, nor when Leibniz was writing his critique of contemporary philosophy (in 1710 or later). As Digby himself wrote, 'It is evident that some bodies are rare and others dense; though obscure how they are so.'[15] Francis Bacon had devoted one of his late treatises to the problem, observing that 'no careful audit, by precise or near-precise calculation, of the quantity of matter and how it is distributed through bodies (in some abundantly, in others sparsely), has yet been set in motion'. Bacon went on to point out that since one barrel of water might be converted into ten barrels of air ('though a hundred [barrels] would be nearer the mark', as he pointed out), then 'it is … impossible to deny that there is ten times more matter in one barrel of water than in one of air'. To understand how this is possible, Bacon dryly commented, 'makes for a difficult enquiry'.[16]

Digby tried to confront the problems of condensation and rarefaction head-on, by simply making these twin phenomena fundamental aspects of his new system of natural philosophy. Leibniz's endorsement notwithstanding, however, it seems that few of his contemporaries were convinced that he had made more headway than other philosophers.

The real breakthrough came later, in the work of Isaac Newton. Newton's solution, however, led Leibniz, in his 'Antibarbarus physicus', to say, 'We can scarcely imagine anything more foolish than this in nature!'[17] In what follows, we will compare Digby's and

[12] G.W. Leibniz, 'Antibarbarus physicus' [*c*.1710–16]; in *G.W. Leibniz: Die Philosophischen Schriften* (ed. Carl Immanuel Gerhardt), 7 vols., Berlin: Weidmann, 1875–1890, vol. 4, 337–44. I have used the translation provided in G.W. Leibniz, *Philosophical Essays* (ed. R. Ariew and D. Garber), Indianapolis: Hackett, 1989, pp. 312–19, 318–19.

[13] Leibniz, *Philosophical Essays*, op. cit. (12), pp. 318–19, refers to Digby's 'main work', which is undoubtedly his *Two Treatises*, op. cit. (10). Digby discusses condensation and rarefaction in the first treatise, *On Body*, especially Chapter 3, pp. 19–32.

[14] Leibniz, *Philosophical Essays*, op. cit. (12), p. 318.

[15] Digby, op. cit. (10), p. 19.

[16] Francis Bacon, 'Historia Densi et Rari' (1622), in *The Oxford Francis Bacon*, vol. 13: *Instauratio Magna: Late Writings* (ed. Graham Rees), Oxford: Clarendon Press, 2000, pp. 37–9. Bacon is still assuming, as was entirely typical at that time, that steam is merely a form of air – water could be converted into air, therefore, by boiling it. But in the process the steam, or 'air', began to take up ten times more room than the water, and so was ten times rarer. For a more wide-ranging discussion of the problem of condensation and rarefaction than that presented here, see Wang, op. cit. (9), pp. 151–69.

[17] Leibniz, *Philosophical Essays*, op. cit. (12), p. 318.

Newton's treatments of rarefaction. Although their approaches are fundamentally different, as we shall see, they were both led to envisage a retiform structure of body – the idea that the fine structure of bodies might be, as Digby wrote, 'like nets or cobwebs'.[18]

Digby on rarefaction

Perhaps surprisingly for present-day readers, the linked concepts of condensation and rarefaction are the effective starting point for Digby's system of natural philosophy. All physical change is held to derive ultimately from the phenomena of condensation and rarefaction. He announced in the preface,

> I have taken my beginnings from the commonest things that are in nature: namely, from the notions of Quantity, and its first differences: which are the most simple and radicall notions that are, and in which all the rest are to be grounded.[19]

The first differences of quantity, for Digby, are its condensation and rarefaction, and he will go on to show how these give rise to all change in nature.

Digby begins with a chapter on the importance of referring to phenomena in the ordinary language used by the rank and file.[20] His second chapter makes the starting point for all discussion of the physical world the concept of 'quantity':

> in our present intended survey of a Bodie, the first thing which occurreth to our sense in the perusal of it, is its Quantitie, bulk, or magnitude: and this seemeth by all mankind to be conceived so inseparable from a body …[21]

Digby goes on from here to claim 'That Quantity or Bignesse, is nothing else but divisibility'.[22] We need not pursue Digby's philosophical qualifications of this suggestion here, but he takes pains to insist that he is merely claiming that quantity is in principle divisible: he does not claim that quantities are actually composed of divisions or parts.[23] So although we talk 'in ordinary discourse, of many parts' of a quantity, we should not lose sight of what is essentially 'the unity of the thing'.[24]

Digby concludes his discussion of quantity with a forceful reiteration of its identification with divisibility:

> So that looking over all the severall specieses [*sic*] of Quantitie; it is evident, our definition of it is a true one, and expresseth fully the essence of it, when we say it is divisibility, or a capacitie to be divided into parts; and that no other notion whatsoever, besides this, reacheth the nature of it.[25]

[18] Digby, op. cit. (10), p. 26.

[19] Digby, op. cit. (10), sig. B3*v*.

[20] Digby writes, 'there are two sorts of language to expresse our notions by: The one belongeth in general to all mankind, and the simplest person, that can but apprehend and speak sense, is as much judge of it as the greatest Doctour in the schools: and in this, the words expresse the things properly and plainly, according to the naturall conceptions that all people agree in making of them'. The other sort is the language developed by scholars 'to serve their private turns'. Digby, op. cit. (10), p. 6.

[21] Digby, op. cit. (10), p. 1. See Chapter 2, 'Of Quantitie', pp. 9–18.

[22] Digby, op. cit. (10), p. 11.

[23] For those interested in Digby's qualifications of the claim that quantity is divisibility, see Martine Pécharman, 'Kenelm Digby on quantity as divisibility', *Vivarium* (2020) 58, pp. 191–218.

[24] Digby, op. cit. (10), p. 17.

[25] Digby, op. cit. (10), p. 18.

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The evident importance of this convergence of quantity and divisibility for Digby is fully revealed in the following chapter, when he introduces his analysis 'Of Raritie and Densitie'.[26]

Digby begins by pointing out that

> it is evident unto us, that there are different sorts of bodies, of which though you take equall quantities in one regard, yet it is evident they will be unequall in another. Their magnitudes may be the same, but their weights will be different; or contrariwise, their weights being equall, their outward measures will not be so.[27]

By way of examples, he compares the weights of a pint pot full of air, water, lead, mercury and gold; and the volumes of equal weights of these same materials. 'But how this comprehension of more body in equall room is effected', Digby says, 'doth not a little trouble Philosophers'.[28]

Digby's solution to the problem reverts back to divisibility:

> if we look well into it, we shall find that the rarer things are as divisible in a lesser Quantity, as the more dense are in a greater: and the same force will break the rarer thing into more and lesser parts, then it will an equall one that is more dense.[29]

Rare bodies are more easily divided than dense bodies. But divisibility is associated with quantity, so rare bodies are those that somehow have more quantity in proportion to their being than dense bodies. At this point, Digby confesses that he 'must touch upon metaphysicks a little more than I desire or intended'.[30]

The metaphysical argument proceeds like this:

> Thus then; remembring how we determined that Quantity is Divisibility: it followeth, that if besides Quantity there be a substance … that thing, if it be condistinguished from its Quantity or Divisibility, must of it self be indivisible: or (to speak more properly) it must be, not divisible …
> This then being so, we have the ground of more or lesse proportion between substance and quantity.[31]

In other words, having characterized quantity as divisible, Digby supposes something else in body which is not divisible, and calls it substance. He can now endorse the Aristotelian characterization of density and rarity:

> the definitions which Aristotle hath given us of Rarity and Density, are the same we drive at: he telleth us, that that body is rare whose quantity is more, and its substance lesse; that, contrariwise dense, where the substance is more and the quantity lesse.[32]

[26] Digby, op. cit. (10), Chapter 3, pp. 19–32.
[27] Digby, op. cit. (10), p. 19.
[28] Digby, op. cit. (10), p. 20.
[29] Digby, op. cit. (10), p. 20.
[30] Digby, op. cit. (10), p. 27. Perhaps it was Digby's recourse to metaphysics that endeared his theory to the arch-metaphysician Leibniz?
[31] Digby, op. cit. (10), p. 27.
[32] Digby, op. cit. (10), p. 28. See Aristotle, *Physics*, IV, Chapter 9, 217a, 21–217b, 11.

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For Digby the agreement with Aristotle was a crucial advantage of his theory.[33]

Perhaps conscious that 'such as are not used to raise their thoughts above Physicall and naturall speculations' might object that substance is something which has magnitude or quantity, rather than something which is ontologically distinct from quantity, Digby reiterates that he is proceeding metaphysically.[34] As he put it,

> if we consider that the composition of quantity with substance, is purely Metaphysicall; we must neccesarily allow the inquiry into the nature of Rarity and Density to be wholly Metaphysicall; seeing that the essence of Rarity and Density standeth in the proportion of quantity to substance; if we believe Aristotle, (the greatest master that ever was, of finding out definitions and notions) and trust to the uncontroulable [i.e. incontrovertible] reasons we have brought in the precedent discourse.[35]

Certainly, Digby's claims under the guise of metaphysics seem to come under the heading of what Thomas Hobbes dismissed as an error: 'Propositions are false, when Abstract Names are copulated with Concrete Names; as … A *Body* is *Magnitude*, A *Body* is *Quantity*…'. Like Digby, Hobbes associated this with 'Aristotles Metaphysicks', though for Hobbes this added to the reasons for rejecting it as false.[36]

It may have been Digby's Aristotelian account of density and rarity, nevertheless, which led Leibniz to see it as establishing an 'absolute condensation and rarefaction'. We can see this, perhaps, when Digby moves from discussing rarity and density 'in abstract … to some particular bodies here among us'.[37]

> For example, [Digby wrote] let us conceive that all the Quantity of the world were in one uniform substance, then the whole universe would be in one and the same degree of Rarity and Density: let that degree, be the degree of water; it will then follow, that in what part soever there happeneth to be a change from this degree, that part will not have that proportion of quantity to its substance, which the quantity of the whole world had to the presupposed uniform substance … which in this case is as it were the standard to try all other proportions by.

Clearly, Digby's 'standard' – the degree (of rarity) of water – is arbitrarily chosen, but as he is conceiving of a standard applicable to 'the whole universe', it suggests that condensation and rarefaction might be treated as absolutes.

Digby tries to confirm his conception by definition:

> for since the definition of a body is, *A thing which hath parts* and quantity is that, *by which it hath parts*; and the first propriety of quantity is, *to be bigger or lesse*, and consequently the first differences of having parts, are to have bigger or lese, more or

[33] On Digby's concern to maintain the Aristotelian credentials of his new system of natural philosophy see John Henry, 'Atomism and eschatology: Catholicism and natural philosophy in the Interregnum', *BJHS* (1982) 15, pp. 211–39.

[34] Digby, op. cit. (10), p. 30.

[35] Digby, op. cit. (10), p. 29. The *Oxford English Dictionary* gives as the first meaning of 'uncontrollable': 'Incontrovertible, indisputable, irrefutable.' It provides examples of this usage from the sixteenth century to the eighteenth.

[36] Thomas Hobbes, *Elements of Philosophy, The First Section, Concerning Body …*, London: Andrew Crooke, 1656, p. 43. Hobbes, of course, was virulently anti-Aristotelian. See Cees Leijenhorst, *The Mechanization of Aristotelianism: The Late Aristotelian Setting of Thomas Hobbes's Natural Philosophy*, Leiden: Brill, 2001.

[37] Digby, op. cit. (10), p. 28.

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> fewer; what division of a body can be more simple, more plain, or more immediate, then to divide it by its Quantity as making it have bigger or lesse, more or fewer parts in proportion to its substance?

And, of course, he also considers how the ordinary person thinks:

> For howsoever witty explications may seem to evade, that the same thing is now greater now lesser; yet it cannot be avoided, but that ordinary men who look not into Philosophy, do both conceive it to be so, and in their familiar discourse expresse it so; which they could not do, if they had not different notions of the substance, and of the quantity of the thing they speak of.[38]

In other words, the ordinary man has no difficulty in saying that a volume of air is now bigger, or smaller; thereby revealing that he easily separates air as a substance from its specific quantity. Finally, in this chapter, he insists that the truth of his theory of density and rarity will be confirmed as he proceeds to show, in the rest of his *Treatise on Body*, how 'all Physicall things and naturall changes do proceed out of the constitution of rare and dense bodies'.[39]

We need not pursue in detail the way all things are said to depend on rarity and density. Anyone familiar with the mode of argumentation used by late scholastic or early modern new philosophers will recognize how Digby works. For example, he begins, in the next chapter, by showing how variations in rarity and density give rise to the four qualities and four elements. Bringing in gravity or weight, Digby argues that if the gravity of a body overcomes its density, the body will collapse and will be perceived to be fluid or moist. Contrariwise, if the density of the body withstands its gravity, the body will preserve its continuity and be perceived as dry. He repeats this exercise for rare bodies, thereby arriving at four sorts of body: dense bodies that are dry or moist, and rare bodies that are dry or moist. He then goes on to claim that a rare dry body will be capable of penetrating into the pores of other bodies, by virtue of its rarity, but this penetrative action is associated with heat, so a rare dry body will also be hot. By similar reasoning, a moist dense body will be cold. Eventually Digby arrives at 'the combinations whereby are constituted fire, aire, water, and earth.'[40]

As a second example, we can consider how Digby uses condensation and rarefaction to explain the natural fall of heavy bodies. In Chapter 10 we are told that the heat of the sun raises two streams in the air – one ascending and one descending – as it causes particles of fire, or the even more rare light, to combine with earthy particles. The resulting combined earth–light, or earth–fire, particle will be rarer than a purely earthy particle. These rarer particles are held to rise up, buoyantly, as denser particles descend to take their place (to avoid a vacuum). Eventually, the rising combined particle will break apart, releasing the particle of light or fire, and leaving a denser earthy particle, ready to descend to take the place of ascending rarer particles. A heavy body placed in these two streams (the ascending rarer stream and a descending denser stream) will descend, since the descending stream of dense particles pushes harder than the ascending stream of rarer particles can. So rarity and density explain why bodies fall to earth.[41] Digby refers other natural phenomena to condensation and rarefaction in similar ways.

38 Digby, op. cit. (10), p. 31.
39 Digby, op. cit. (10), p. 31.
40 Digby, op. cit. (10), p. 38.
41 Digby, op. cit. (10), pp. 94–106.

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Treating these linked phenomena as fundamental ways of change, from which all other kinds of physical change were held to follow, might be another reason why Leibniz said Digby 'retained an absolute condensation and rarefaction'. Digby did not simply regard variation of density and rarity as just another problem to be solved, but treated it as the foundational starting point for his physics.

Digby's rejection of alternative accounts

What is much more important for understanding subsequent developments, however, is Digby's rejection of the two most prominent rivals to his Aristotelian (or absolute?) way of explaining condensation and rarefaction. He focuses on what Leibniz would have called mechanical philosophies, but which Digby would have thought of as atomist or corpuscularian philosophies – that is to say, philosophies based on the assumption that all bodies were composed of invisibly small particles which only differed from one another in shape, size, arrangement and motions. These new philosophies were the outcome of the revival of ancient atomism, following on from the Renaissance recovery of Lucretius' *De rerum natura* (*c*.55 BC), but with many original features.[42] These new kinds of corpuscularian philosophy were developed along two main lines: plenist and vacuist.[43] Plenism assumed that the world system was completely full of matter; the particles that constituted all things were considered to be crowded together with no gaps between, and void space was held to be a categorical impossibility. The major representative of this view among Digby's contemporaries was René Descartes, for whom extension signified matter.[44] Vacuism was closer to the ancient atomist position and assumed that the particles which constituted all things existed in a universal void space. This view was chiefly promoted in Digby's day by Pierre Gassendi.[45]

Digby takes on the plenists first. How can they explain that some matter is lighter than other matter? If they claim it is due to the division of matter into smaller particles, they must also assume that these lesser particles are more widely separated from one another. If they are not, then their division into lesser parts would count for nothing, because their lack of separation would make them tantamount to being a continuous solid. If these lesser particles are separated, however, we have to ask what other body fills up the spaces between them. Taking the example of water as a rare medium, Digby suggests that we suppose that air is keeping the particles of water separated from one another.

But this raises the question whether air is lighter than water. If it is not, then the combination of water with air between its particles is just as dense as water on its own. More to the point, the water–air combination will be as dense as any other material, lead, mercury, gold or whatever. Digby is writing long before Lavoisier and John Dalton and the idea of qualitatively different atoms. The lingering influence of Aristotelian hylomorphism still pertained, and Digby, along with all his contemporary new philosophers, still believed there is only one kind of matter. Gold differs from lead, and from water,

[42] See Catherine Wilson, *Epicureanism at the Origins of Modernity*, Oxford: Clarendon Press, 2008; and Stephen Greenblatt, *The Swerve: How the Renaissance Began*, London: Vintage, 2012.

[43] 'Atomism', strictly speaking, requires the particles to be indivisible. Use of 'corpuscularian' avoids this connotation, and is generally more correct when discussing the natural philosophies of early modern thinkers. 'Atomism' also implies (on the ancient Greek model) a belief in void space between the atoms, which again is by no means a given among early modern thinkers.

[44] That is to say, for Descartes, if a thing is extended in three dimensions, it must be a body. Descartes's major work, published the same year as Digby's *Two Treatises*, was *Principia Philosophiae*, Amsterdam: Elsevier, 1644. Digby knew Descartes, however, and was aware of his philosophical thinking even before Descartes published his *Principia*.

[45] Pierre Gassendi, *Syntagma Philosophiae Epicuri …*, Lyon: Guillaume Barbier, 1649. Again, Digby knew Gassendi, the main points of whose attempts to revive ancient Epicureanism were well known even before he published.

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because their constituent particles are supposed to be of different sizes and shapes, and to be arranged differently, but they are all composed of prime matter, the one and only kind of matter there is.

The only way water particles, separated by air particles, can be said to be rarer than water particles which are not so separated is to assume that the air is itself rarer than the water. In which case, as Digby points out, 'it must be, because every part of aire hath again its parts more severed by some other body, then the parts of water are severed by aire'.[46] This other body must have its particles held apart by a supposedly still thinner body. Since an infinite regress is not possible we must eventually come to a body 'whose little parts filling the pores and spaces between the parts of the others, have no spaces in themselves to be filled up'.[47]

> But as soon as you acknowledge such a body to be lighter and rarer then all the rest, [Digby points out,] you contradict and destroy all you said before. For by reason of its having no pores, it followeth by your rule, that the little parts of it must be as heavy, if not heavier, then the little parts of the same bignesse of that bodie whose pores it filleth.[48]

In other words, we are back to a body which must be as dense as lead, or perhaps denser. And likewise, the water we started with must be 'as heavie and as dense as lead'.[49] If there is only one kind of matter (as was generally assumed), and there is no empty space anywhere (as the plenists insisted), then water, or air, must be as dense and as heavy as lead.

This seems so obvious that it might seem hard to imagine that any philosopher could have seriously offered such an account of rarefaction. In fact, not just any philosopher, but Descartes himself did propose just such an unworkable account of rarity.

In his *Principia Philosophiae*, Descartes dismissed 'some men so subtle that they distinguish the substance of a body from its quantity', which certainly included Digby.[50] But his own account of rarefaction, which he explicitly says 'cannot be intelligibly explained in any other way', depends upon the parts of the rarefying body spreading apart while the spaces between the parts 'are filled by other bodies'.[51] Descartes neglects to say more about these other bodies, but since Descartes believes there is only one kind of matter, albeit manifested as three 'elements' of differently sized particles, these other bodies must be just as dense as the body that is supposedly becoming rarer.[52] Descartes cannot explain, therefore, how a volume of air can be lighter in weight than the same volume of lead. If lead and air are both considered to be continuous entities, with no gaps or voids in their substance, then they must both be equally dense, since they are made of the same matter.

Having exposed the unworkability of the plenist account, Digby immediately turned to the vacuist account of rarity. The assumption here is that a body is rarer than another because its particles are separated by greater distances in the surrounding void space. Predictably, Digby repeats the Aristotelian arguments against void space, in Book IV of

46 Digby, op. cit. (10), p. 23.

47 Digby, op. cit. (10), p. 23.

48 Digby, op. cit. (10), p. 23.

49 Digby, op. cit. (10), p. 23.

50 René Descartes, *Principles of Philosophy*, trans. V.R. Miller and R.P. Miller, Dordrecht: Reidel, 1983, Part II, §5, p. 41. Leibniz links Digby's 'absolute' treatment of condensation and rarefaction to Honoré Fabri. Leibniz, *Philosophical Essays*, op. cit. (12), p. 318. Whether Descartes also had other 'men' in mind is unknown to me.

51 Descartes, op. cit. (50), Part II, §7, 42, and §6, 41.

52 We do not need to go into the details of Descartes's theory of three elemental forms here, but they are all made of the same matter. See Descartes, op. cit. (50), Part III, §§48–52.

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his *Physics*. Digby acknowledges that the Aristotelian objection that motion is impossible in a vacuum has been dismissed as irrelevant by contemporary vacuists, on the ground that they do not suppose particles 'floating up and down without touching anything' (which would imply action at a distance between the particles), and so moving in a vacuum.[53] They only suppose interstitial void space; that is to say, small separated voids between particles which are held to be touching one another at their extremities (so, when spherical particles are closely packed together, the voids will be confined to the places which the spheres cannot fill). Certainly, this was the line taken by Gassendi.[54]

Digby's response to this is highly significant. Using figures taken from Galileo and Marinus Ghetaldus, Digby tells his readers that water is four hundred times heavier than air, and that gold is nineteen times heavier than water. Accordingly, gold is 7,600 times heavier than air. It must be supposed, therefore, that the proportion of matter to vacuum in a portion of air must be 1 in 7,600. Indeed, the ratio must be even greater because we know from the behaviour of gold that it is itself highly porous (gold leaf, for example, can be seen to be translucent, and so light can pass through it). This means, therefore, that air 'would be lyable to have little parts of its body swimme in those greater vacuities; contrary to what they [atomists] strive to avoid'.[55] Consequently, the vacuist account does run up against Aristotle's objection to motion in a vacuum. In cases considering the movement of bodies through fire or aether, which were held to be much rarer than air, the bodies would be moving through even more extensive void spaces, contrary to what Aristotle had said was possible. But, even leaving these considerations aside, Digby says, the vacuists are committed to so much vacuum in air that Aristotle's objection applies, and motion even through the air, of small bodies at least, would be impossible.[56]

Digby's second argument against vacuist accounts of rarity is that rare bodies can be concentrated together without losing their rarity. When smiths and 'glassemenders' concentrate their fires into a narrow space, we might expect (on the vacuist account) that the fires would fill each others' void spaces, with the result that we would be left with a fire that, somehow, was no longer rare. This doesn't happen, of course, and the extra efficacy of the smiths' concentrated fires shows that they are as penetratingly rare as they ever were.[57]

Arguably, the most telling of Digby's objections to the vacuist account is the third:

> Thirdly, if such vacuities were the cause of rarity, it would follow, that fluide bodies being rarer then solid ones, they would be of themselves standing, like nets or cobwebs: whereas contrariwise, we see their natures are to run together, and to fill up every little creek and corner: which effect, following out of the very nature of the things themselves; must needs exclude vacuities out of that nature.[58]

Digby had already used the image of a net in his first objection, comparing the density of air with gold:

[53] Digby, op. cit. (10), p. 24. Aristotle offers a number of arguments against the possibility of motion through a supposedly void space in *Physics*, IV, Chapter 8.

[54] Pierre Gassendi, *Syntagma Philosophicum* [1649], in Gassendi, *Opera Omnia* (Lyon: Habert de Montmor, 1658), vol. 1, pp. 192–6. For further discussion, see Margaret J. Osler, *Divine Will and the Mechanical Philosophy*, Cambridge: Cambridge University Press, 1994, pp. 184–6.

[55] Digby, op. cit. (10), p. 25. Digby refers us to Galileo's *Discorsi … intorno a due nuove scienze*, Leiden: Elzevier, 1638, p. 81; and Marinus Ghetaldus, *Promotus Archimedis*, Rome: Luigi Zanetti, 1603.

[56] Digby, op. cit. (10), pp. 25–6.

[57] Digby, op. cit. (10), p. 26.

[58] Digby, op. cit. (10), p. 26.

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> But according to this rate, without pressing the inconvenience any further; the aire will by this reckoning appear to be like a net, whose holes and distances, are to the lines and thrids, in the proportion of 7600 to one …[59]

Clearly, Digby was trying to envisage the structure of matter if the solid parts of it were, as the vacuists claimed, separated by intervening void spaces. The image that came to his mind was of a net-like or web-like structure. He clearly did not think of atoms or corpuscles suspended separated in space without touching one another – he did not envisage an array of individual particles spaced out from one another in the void. Such an array would require actions at a distance between the spaced-out particles, and that seemed to be beyond his imagination.

From Robert Boyle to Isaac Newton

By the time Newton became exercised by the problem of condensation and rarefaction, in the late 1670s, the natural-philosophical landscape had changed dramatically. The experimental results achieved by Robert Hooke and Robert Boyle using the newly invented air-pump revealed variations in density far far greater than Digby's '7600 to one'.[60]

In his *Defence of the Doctrine Touching the Spring and Weight of the Air* of 1662, Robert Boyle presented his readers with the same alternative accounts of rarity and density that had been discerned by Digby. His summary is worth quoting in full:

> That Rarefaction (as also Condensation) being amongst the most obvious Phaenomena of Nature, there are three (and for ought we know but three) wayes of explicating it: For, either we must say with the Atomists and Vacuists, that the Corpuscles whereof the rarefied body consists do so depart from each other, that no other substance comes in between them to fill up the deserted spaces that come to be left betwixt the incontiguous Corpuscles; or else we must say with divers of the ancient Philosophers, and many of the moderns, especially the *Cartesians*, that these new Intervals produced betwixt the Particles of the rarefied body are but dilated Pores, replenished, in like manner as those of the tumid Spunge are by the imbibed water, by some subtile Aethereal substance, that insinuates it self betwixt the disjoyned Particles: or, lastly, we must imagine with *Aristotle* and most of his followers, that the self-same body does not onely *obtain* a greater space in Rarefaction, and a lesser in Condensation, but adequately and exactly *fill it*, and so when rarefied acquires larger dimensions without either leaving any vacuities betwixt its component Corpuscles, or admitting between them any new or extraneous substance whatsoever.[61]

Being engaged here to defend himself against an Aristotelian opponent, Boyle explicitly dismissed 'the Aristotelean way of Rarefaction' as unintelligible.[62] He was less forthcoming, however, about the Cartesian and vacuist accounts. It is perfectly clear that Boyle himself believed in the reality of void space, but he always remained very coy about discussing the theoretical implications of this position. But in his earlier work on these

[59] Digby, op. cit. (10), p. 25.

[60] Digby, op. cit. (10), p. 25. On the impact of the air-pump on natural philosophy see Shapin and Schaffer, op. cit. (3).

[61] Robert Boyle, *Works* (ed. Michael Hunter and Edward B. Davis), London: Pickering & Chatto, 1999, vol. 3, p. 42.

[62] Boyle, op. cit. (61), vol. 3, pp. 41, 42, 45, 46, 65. Boyle is responding to the objections of Franciscus Linus SJ, *Tractatus de Corporum Inseparabilitate* …, London: John Martyn *et al.*, 1661.

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matters, *New Experiments Physico-Mechanical, Touching the Spring of the Air and its Effects* (1660), Boyle had effectively dismissed the Cartesian position, albeit in a roundabout way.

Boyle linked Cartesianism to an aetherist approach; that is to say, to an approach which assumed the existence of an all-pervasive aether which was held to fill all the space between bodies (thereby ensuring that void space never occurred). 'That most ingenious Gentleman, Monsieur Des Cartes', he wrote, held

> That the Air is nothing but a Congeries or heap of small and (for the most part) of flexible Particles; of several sizes, and of all kinde of Figures which are rais'd by heat (especially that of the Sun) into that fluid and subtle Etheriall Body that surrounds the Earth.[63]

This had become a common aspect of contemporary Cartesianism, but it should be noted that this supposed aether was now held to be tenuous and rare in its own right (a position which, as we noted earlier, Descartes's three-element theory could not accommodate).

Where Digby had been correct to note that what Descartes called his 'First Element' must be every bit as dense as his so-called second and third elements, later Cartesians had slipped (illegitimately) into assuming that the aether (equivalent to Descartes's first element) must be thinner or rarer than other bodies.[64] Accordingly, these latter-day Cartesians could glibly insist that the air-pump could not produce a vacuum, because the aether was sufficiently subtle and penetrating that it could pass through the glass of the chamber of the air-pump. Boyle was not amused:

> And as for the Allegations above mention'd, they seem to prove but that the Receiver [of the air-pump] devoy'd of Air, *May* be replenish'd with some such Etherial Matter, as some Modern Naturalists write of; but not that it really *is* so. And indeed to me it yet seems, that as to those spaces which the *Vacuists* would have to be empty, because they are manifestly devoid of Air; and all grosser Bodies, the *Plenists* (if I may so call them) do not prove that such spaces are replenish'd with such a subtle Matter as they speak of, by any sensible effects, or operations of it (of which divers new Tryals purposely made, have not yet shown me any) but onely conclude that there must be such a Body, because there cannot be a Void. And the reason why there cannot be a Void, being by them taken, not from any Experiments, or Phaenomena of Nature, that clearly and particularly prove their Hypothesis, but from their notion of a Body, whose Nature, according to them, consisting onely in extension …[65]

Clearly, the self-professed Baconian experimentalist Robert Boyle was unimpressed by these Cartesian attempts to undermine the results of his air-pump experiments by recourse to an empirically undetectable aether.[66] Undaunted, therefore, Boyle continued

[63] Boyle, op. cit. (61), vol. 1, p. 166.

[64] Possibly, they were inspired to make this move by the way that Descartes glibly referred to things being 'rarefied'. See, for example, Descartes, op. cit. (50), Part III, §100, p. 138, and §102, p. 139. It seems possible that Descartes himself never fully worked out the relationship between his elements and the aether. The first element, consisting of the smallest and most penetrative particles, ought to constitute the aether, but at Part III, §52, p. 110, he says the heavens are composed of the second element; while at Part III, §100, p. 139, he writes, 'we include in the third element all the spots of the Sun and other stars, and also all the aether surrounding them'. Whichever of the elements is taken to constitute the aether, the argument presented here against the aether's supposed rarity still stands.

[65] Boyle, op. cit. (61), vol. 1, p. 198.

[66] Blaise Pascal had also complained about the experimentally inaccessible nature of supposed aethers in his *Expériences nouvelles touchant le vide* of 1647, going so far as to accuse some contemporaries, including Descartes, of

with his experiments. In 1670 he published *A Discovery of the Admirable Rarefaction of Air (even without Heat)*. In repeated experiments listed here under the heading 'Experiment III', Boyle reported that he had at worst rarefied air 2,744 times, and at best 'at least 13000 times'.[67] Indeed, in the conclusion to this work he claims,

> the greatest, to which we have advanc'd it [air] by Rarefaction, after having taken notice, that, according to the least estimate of any recited in the fore-going Experiments, the extension of the same quantity of Air, is as 1 to 2744, or thereabouts, and if, instead of the moderatest, we [have] taken the greatest Expansion of the Air, being (leaving out the odd hundreds to make the rounder number) as 13000 to 1, when the uncomprest Air was highly rarefied, that number being multiplied by 40, because of the forementioned compression of the Air, will amount to 520000, for the number of times, by which the Air at one time exceeds the same portion of Air at another time.[68]

We can turn now to Isaac Newton, who was one of Boyle's greatest admirers. In the early part of Newton's career as a natural philosopher, he fully embraced the concept of an undetectable aether. This changed, however, not long after Newton and Boyle had a serious conversation (in 1678 or early 1679) which must have included discussion of the problem of condensation and rarefaction. We can infer that this took place from the letter Newton wrote to Boyle in February 1679, in which he referred to their previous discussion, and in which he developed a theory of chemical interactions which relied heavily upon the phenomenon of rarefaction.[69] It is clear from his own comments on this theory that Newton was very dissatisfied with it, and it turned out to be the last time for decades that his natural philosophy assumed the existence of an aether.[70] Shortly after writing this letter, Newton's natural philosophy underwent a sea change in which interparticulate forces of attraction and repulsion took the place of aethers in explaining physical change.

Newton, rarefaction and retiform structures

Shortly after writing his letter to Boyle of February 1679, Newton wrote a brief, unfinished, but revealingly important manuscript in which his new style of physics is adumbrated.[71] It is untitled, but known by the title of its two chapters as 'De Aere et

filling the Torricellian vacuum with 'a matter which subsists only in their imagination'. See Daniel C. Fouke, 'Pascal's physics', in Nicholas Hammond (ed.), *The Cambridge Companion to Pascal*, Cambridge: Cambridge University Press, 2003, pp. 75–101, esp. 78. Incidentally, scholarship on Pascal's experiments provides another example of failing to note the historical importance of the problem of condensation and rarefaction. Although Pascal scholarship necessarily refers to the issue of condensation and rarefaction, it largely passes over it to focus on the debate over the existence, or otherwise, of void space, and of atmospheric pressure.

[67] Boyle, op. cit. (61), vol. 6, p. 374.

[68] Boyle, op. cit. (61), vol. 6, p. 387.

[69] Robert Boyle, *Correspondence* (ed. Michael Hunter, Antonio Clericuzio and Lawrence M. Principe), London: Pickering & Chatto, 2001, vol. 5, pp. 141–9. Also H.W. Turnbull *et al.* (eds.), *The Correspondence of Isaac Newton*, Cambridge: Cambridge University Press, 1959–77, vol. 2, pp. 288–96.

[70] Newton's evident dissatisfaction is shown in comments at the beginning and the end of the letter. Aethers dropped out of Newton's mature physics, as it was developed in the *Principia Mathematica*. He reintroduced the concept of an aether in a group of speculative 'Queries' which he added to the 1717 edition of the *Opticks*, but he never discussed, much less developed, this version of the aether subsequently.

[71] The date of this manuscript is disputed. A. Rupert Hall and M. Boas Hall (eds.), *Unpublished Scientific Papers of Isaac Newton*, Cambridge: Cambridge University Press, 1962, pp. 187–9, suggest sometime between 1673 and 1675.This strikes me as implausible for a number of reasons; not least is the fact that it requires Newton to abandon the interparticulate physics developed here and to return to aetherist explanations in subsequent writings. I have accepted the date suggested by Westfall: 1679, shortly after the aetherist letter to Boyle of 28 February 1679.

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Aethere', and it is easy to see the influence on it of Hooke's and Boyle's air-pump experiments. In the chapter headed 'De Aere' we read,

> The whole weight of the incumbent atmosphere by which the air here close to the Earth is compressed is known to philosophers from the Torricellian experiment, and Hooke proved by experiment that the double or treble weight compresses air into the half or third of its space, and conversely that under a half or a third or even a hundredth or a thousandth part of that weight [the air] is expanded to double or treble or even a hundred or a thousand times its normal space, which would hardly seem to be possible if the particles of air were in mutual contact; but if by some principle acting at a distance [the particles] tend to recede mutually from each other, reason persuades us that when the distance between their centres is doubled the force of recession will be halved, when trebled the force is reduced to a third and so on, and thus by an easy computation it is discovered that the expansion of the air is reciprocal to the compressive force.[72]

Newton goes on to make clear that what he is supposing here is a repulsive force operating between the particles of air without there being any material medium between the particles. Consequently, the repulsive forces are said to be operating at a distance. The weight of the atmosphere keeps the air particles compressed together, but if that compressive force is reduced, there is an entirely spontaneous 'expansion of the air' due to the supposed repulsive forces between the particles.

'Moreover', he adds, 'air does not only seek to avoid bodies, but bodies also tend to fly from each other.'[73] In other words, it is not just particles of air which are endowed with mutually repelling forces, but the particles of all bodies are assumed to repel one another. Presumably Newton made this assumption because he fully accepted the consensual view that the corpuscles constituting all bodies differed only in shape, size, arrangement and their motions; the matter itself of the corpuscles was always the same, as was noted above. Consequently, if particles of air repel other particles, then the particles of other materials, made of the same matter, must also repel other particles.[74]

It is important to recognize just how remarkable these speculations of Newton's were. Although the extreme rarefaction of air that was possible with the air-pump seemed to suggest the particles must be spread widely apart from one another, this entailed acceptance of what had always been regarded as the completely untenable idea of action at a distance.[75] Although Digby himself had admitted that the vacuist account of rarefaction – in which the constituent particles of a body were spread farther apart from one another through the surrounding void – was 'very easie and intelligible', it was, as we have seen, completely unacceptable.[76] Even the vacuists themselves refused to introduce action at a distance into their accounts. Walter Charleton, following his mentor Gassendi, spoke only

See R.S. Westfall, *Force in Newton's Physics*, London: Macdonald, 1971, p. 375, pp. 409–10. See also his *Never at Rest: A Biography of Isaac Newton*, Cambridge: Cambridge University Press, 1980, pp. 374–6. For a much fuller argument in favour of this later date see John Henry, 'Newton's "De Aere et Aethere" and the introduction of interparticulate forces into his physics', *Annals of Science* (2023) 80(3), pp. 232–67.

72 Hall and Hall, op. cit. (71), pp. 223–4 (Latin pp. 216–17).

73 Hall and Hall, op. cit. (71), p. 222 (Latin p. 215).

74 For further explicit discussion of actions at a distance in 'De Aere' see Hall and Hall, op. cit. (71), pp. 223 (Latin p. 216), 224 (217), 225 (218).

75 On the contemporary unacceptability of action at a distance see John Henry, 'Newton and action at a distance', in Eric Schliesser and Chris Smeenk (eds.), *The Oxford Handbook of Newton*, Oxford: Oxford University Press, 2019, online at https://doi.org/10.1093/oxfordhb/9780199930418.013.17.

76 Digby, op. cit. (10), p. 25.

of interstitial voids, and rarefying particles moving into ‘a more lax and open contexture’. The implication was that the particles were still in contact with one another.[77] Boyle, for his part, simply refused to offer any account at all of how such extreme rarefactions were possible.[78] He was content merely to recount the experiments which demonstrated extreme rarefaction, but offered no hypothetical underpinning. The near unanimous consensus of the day (as it had been since the Middle Ages) was that bodies could only act upon one another by contact. The suggestion that there might be such a phenomenon as action at a distance – that is to say, action of one body on another without material contact – was regarded as utterly impossible.[79]

Thanks to Boyle’s work, Newton knew that the particles could not still be in contact, as Charleton and Gassendi had earlier supposed (they were both writing before the air-pump experiments). If Boyle refused to draw any conclusions as to what was implied, Newton was bold enough to conclude that the age-old strictures against actions at a distance must simply be wrong. The extreme rarefactions achievable in the chamber of the air-pump, Newton inferred (‘reason persuades us’, he wrote), led him to suppose that action at a distance must be possible.[80]

Asserting the possibility of actions at a distance was so outrageous, however, that Newton quickly abandoned this manuscript. This brief speculative excursion into a physics of interparticulate repulsive forces might never have proceeded any further. It just so happened, however, that a few years after abandoning ‘De Aere et Aethere’, Newton found himself, at the importuning of Edmond Halley, developing the universal principle of gravitation – a principle which also depended upon the assumption of action at a distance, but this time of an attractive force.[81] This evidently gave Newton renewed confidence to return to his physics of interparticulate forces acting at a distance.

In a draft ‘Conclusio’ which Newton wrote for the *Principia* in 1687, he made it clear that he saw the foregoing discussion of gravity as an exemplary treatment of the kind of physics of interparticulate forces that he hoped to develop. Consider, for example, the opening words:

> Hitherto I have explained the System of this visible world, as far as concerns the greater motions which can easily be detected. There are however innumerable other local motions which on account of the minuteness of the moving particles cannot be detected … Whatever reasoning holds for greater motions, should hold for lesser ones as well. The former depend upon the greater attractive forces of larger

[77] Walter Charleton, *Physiologia Epicuro-Gassendo-Charltoniana*, London: Thomas Heath, 1654, p. 26. For a fuller account of Gassendi’s and Charleton’s attempts to explain rarefaction without invoking action at a distance see Wang, op. cit. (9), pp. 165–6.

[78] See, for example, Boyle, op. cit. (61), vol. 1, p. 166, where he writes that he is concerned only to establish that the air has ‘spring’, but not to assign an adequate cause of it.

[79] The consensus was only ‘near unanimous’ because, thanks largely to the revival of natural magic by Marsilio Ficino, there were some before Newton who countenanced the possibility of action at a distance. See Henry, op. cit. (75).

[80] It might be objected that at one point in ‘De Aere’ Newton wrote, in an evident fit of pusillanimity, that the cause of the mutual repulsion between particles might be an aether. Hall and Hall, op. cit. (71), p. 223 (Latin p. 216). Accordingly, it might be argued, he did not really accept actions at a distance. The important thing to note in this regard, however, is that the comment about the possible role of an aether was crossed out. Newton allowed the comments about actions at a distance to stand throughout, but he struck out the comment which would have undermined these claims by somehow attributing the interparticulate repulsion to an aether. For a fuller discussion see Henry, op. cit. (71).

[81] Halley pleaded with Newton, from 1684, to write what became the *Philosophiae Naturalis Principia Mathematica*, London: Royal Society, 1687. See George E. Smith, ‘The *Principia* from conception to publication’, in Schliesser and Smeenk, op. cit. (75), at https://doi.org/10.1093/oxfordhb/9780199930418.013.37.

> bodies, and I suspect that the latter depend upon the lesser forces, as yet unobserved, of insensible particles. For, from the forces of gravity, of magnetism, and of electricity it is manifest that there are various kinds of natural forces and that there may be still more kinds is not to be rashly denied. It is very well known that greater bodies act mutually upon each other by those forces, and I do not clearly see why lesser ones should not act on one another by similar forces.[82]

Similarly, a little later he reiterates: 'all the more secret motions of the least particles are no less brought into being than are the motions of greater bodies which as we saw in the foregoing derived from the laws of gravity.'[83] It was at this point that Newton turned to the phenomenon of rarefaction, explaining, as he had done in 'De Aere et Aethere', that it resulted from repulsive forces between particles. There is no reminder here, however, of the extreme rarefactions achieved by Hooke and Boyle. Newton had avoided any explicit mention of actions at a distance throughout the *Principia*, although, as the reactions of mechanical philosophers such as Christiaan Huygens, G.W. Leibniz, and Bernard Le Bovier de Fontenelle clearly show, it was recognized on publication that Newtonian gravity was, albeit implicitly, an action at a distance.[84] Be that as it may, it seems clear that Newton intended to continue to avoid explicit mention of action at a distance in the 'Conclusio', and so, rather than refer to Boyle's extreme rarefactions, he merely pointed out that gold was nineteen times denser than water (just as Digby had done forty years earlier), and that even gold has an open structure involving void pores.[85]

Accordingly, Newton was able to suggest that bodies might be structured, as Digby had earlier ridiculed, 'like nets or cobwebs':

> these particles will not collect together in the composition of natural bodies like a heap of stones, but they coalesce into the form of highly regular structures almost like those made by art, as happens in the formation of snow and salts. Undoubtedly, following the laws of geometry they can be formed into very long and elastic rods into retiform particles (*in particulas retiformes*), and by the composition of these into greater particles, and so at length into perceptible bodies.[86]

Where Digby had envisaged corpuscles that must be like collapsible threads ('thrids', as he wrote), Newton now envisaged particles like rigid rods, capable of standing up in retiform structures.[87]

Apart from the difference in rigidity, Digby's and Newton's conceptions differed in another important way. Digby had absolutely no conception of the kind of force that Newton would later take for granted in his *Principia*, and the 'Conclusio' with which he intended to end it. Newton's attractive and repulsive forces, modelled on gravity, and on magnetic and electrical

[82] Hall and Hall, op. cit. (71), p. 333 (Latin p. 321).

[83] Hall and Hall, op. cit. (71), p. 341 (Latin p. 327).

[84] See Alexandre Koyré, 'Huygens and Leibniz on universal attraction', in *Newtonian Studies*, London: Chapman & Hall, 1965, pp. 115–38; and Bernard Le Bovier de Fontenelle, *The Elogium of Sir Isaac Newton*, London: Tonson *et al.*, 1728.

[85] At one point, discussing repulsive forces, Newton writes, 'distant ones [particles] seek to separate from one another'; otherwise he merely talks of attractive and repulsive forces, leaving it implicit that these act at a distance. Hall and Hall, op. cit. (71), p. 341 (Latin p. 328).

[86] Hall and Hall, op. cit. (71), p. 341 (Latin p. 328). R.S. Westfall long ago noted Newton's discussion of bodies composed 'on the pattern of nets'. See Westfall, *Force in Newton's Physics*, op. cit. (71), pp. 384–5. He also mentioned the 'particulas retiformes' in his biography of Newton, *Never at Rest*, op. cit. (71), pp. 388–90, although here he linked them to Newton's alchemical work rather than to his attempts to understand rarefaction.

[87] Digby, op. cit. (10), p. 25.

attraction and repulsion, were conceived to be immaterial and necessarily acting at a distance (that is to say, without material contact). Digby's concept of force was completely different, and much more limited. Digby would have subscribed to the standard view of force, as assumed also in Descartes's new philosophy, and as insisted upon, for example, by Leibniz in his 'Antibarbarus physicus' and other works. The standard concept of force was force of impact, or force of collision. A body was capable of imparting force to another body only if it was moving and crashed into that other body. The only force was force of impact.

This is clear, for example, from the 'Antibarbarus physicus', where Leibniz wrote, 'true corporeal forces are only of one kind, namely, those arising through the impression of impetus (as for example, when a body is flung forward)'.[88] Accordingly, when Newton used the word 'force' to refer to attractions and repulsions, he was misusing the word. As Leibniz objected, 'It pleases others to return to *occult qualities* or to *Scholastic faculties*, but since those crude philosophers and physicians [see that] those [terms are] in bad repute, changing the name, they call them forces.'[89]

In accordance with this, Digby assumed that the vacuist account simply required the air particles themselves to be elongated like threads, and to be connected to one another with 'holes and distances' between them.[90] For Newton, however, it was the immaterial forces of repulsion (in this case) which resulted in the open net-like structure of the particles. It is, he wrote, 'through the forces' that particles 'coalesce into the form of highly regular structures'. So the particles like 'very long and elastic rods' are formed that way by the forces, 'following the laws of geometry'.[91] The fact that Newton did not simply rely on the forces 'by which contiguous bodies cohere, and distant ones seek to separate from one another', to produce bodies whose particles were separated from one another in void space, but instead described the forces creating long rod-shaped material particles, suggests that he was trying to disguise the role of forces acting at a distance in his account. There is no equivalent discussion of this kind in 'De Aere et Aethere', for example. In that earlier work Newton provides two diagrams in which the mutually repelling particles are simply depicted as small circles, or dots, set apart in a regular array by the supposed invisible forces operating at a distance between them.[92] The diagrams depict particles separated in space, not particles formed into rod-like, or net-like, structures.

The same caution that we see in the 'Conclusio' was also exercised in the extended draft preface he wrote for the *Principia*, but which, like the 'Conclusio', he abandoned (in favour of the shorter preface of the published book). Having said in the extended preface that when various particles 'are at a distance they repel each other', Newton wrote,

> such forces account for the fact that the particles of bodies do not collect together like a heap of stones, but like snow and salts coalesce into regular figures. From the very smallest particles bigger ones are formed, and from these the largest ones, all in a lattice structure [*per texturas retiformes*].[93]

[88] Leibniz, *Philosophical Essays*, op. cit. (12), p. 313; see also 317: 'no body is moved except through the impulse of a body touching it'; and 319: 'force is exercised only through an impressed impetus.'

[89] Leibniz, *Philosophical Essays*, op. cit. (12), p. 313; see also 315: 'But some people have added qualities which they have also called faculties, virtues, and most recently, *forces*.' Leibniz makes the same objection in his famous correspondence with Samuel Clarke: 'the occult qualities of the schools; which some men begin to revive under the specious name of forces'. H.G. Alexander (ed.), *The Leibniz–Clarke Correspondence*, Manchester: Manchester University Press, 1956, Leibniz's Fifth Paper, §113, p. 92.

[90] Digby, op. cit. (10), p. 25.

[91] Hall and Hall, op. cit. (71), p. 341 (Latin p. 328).

[92] Hall and Hall, op. cit. (71), pp. 224, 225 (Latin 217, 218). One of these diagrams is crossed out, and not discussed in the text.

[93] Hall and Hall, op. cit. (71), p. 306 (Latin p. 303).

The particles are said to display a net-like structure, although it is the immaterial repulsive forces which are responsible for that structure. Again, there is no hint of the extreme rarefactions achieved in the air-pump experiments; when Newton talks of bodies differing 'markedly among themselves in density', he merely says 'just as water may be 19 times rarer than gold'.[94] Once again, it seems that Newton does not want to draw too much attention to the fact that he is assuming the operation of forces which act at a distance.

It seems, then, that Newton first turned to the idea of interparticulate repulsive forces in his 'De Aere et Aethere' of 1679, in order to explain the extreme rarefactions that were possible using Hooke's and Boyle's air-pump. Soon after, inspired by his work on the attractive force of gravity in the *Principia*, he further developed the idea of interparticulate forces in drafts that he intended to add to his great work. In these drafts, however, he played down the emphasis on action at a distance, which had been such a striking feature of 'De Aere', and emphasized instead the net-like structures of bodies.

It is perhaps significant also that from 1679 through to the early 1680s and even after the publication of the *Principia*, Newton focused much of his efforts in alchemy on reproducing what he called 'the net', an alloy which he described as 'like a net wth hollow work as twere cut in'.[95] Newton's investigation of 'the net' in alchemy was certainly driven by an alchemical agenda, but it is possible that his experimental reproduction of this alloy, with a net-like appearance on its surface, might have encouraged his speculations about invisible net-like structures in bodies as a way of understanding rarefaction.

It was only when Newton allowed himself to write again in a more speculative mode, in the *Quaestiones* that he added to the end of the 1706 *Optice*, that he wrote again of the extreme rarefaction of air and what it implied. In *Quaestio 23* we read,

> The Particles when they are shaken off from Bodies by Heat or Fermentation, so soon as they are beyond the reach of the Attraction of the Body, receding from it, and also from one another with great Strength, and keeping at a distance, so as sometimes to take up above a Million of Times more space than they did before in the form of a dense Body. Which vast Contraction and Expansion seems unintelligible, by feigning the Particles of Air to be springy and ramous, or rolled up like Hoops, or by any other means than a repulsive Power.[96]

Evidently, Newton would have now included the 'very long and elastic rods' of the 'Conclusio' as no better than the coiled springs assumed by some to be the cause of the 'spring' of the air. As he said, nothing fits the bill, except 'repulsive Power'.

Conclusion

The conjoined problem of condensation and (especially) rarefaction, as Digby admitted, did 'not a little trouble Philosophers', and had done so since ancient times.[97] Digby tried to sidestep the problems by making the phenomena of rarity and density fundamental aspects of his new natural philosophy. He tried to present condensation and rarefaction not as problems to be solved but as taken-for-granted foundational natural

[94] Hall and Hall, op. cit. (71), p. 306 (Latin p. 303).

[95] See William R. Newman, *Newton the Alchemist*, Princeton, NJ: Princeton University Press, 2019, pp. 358, 286–91, 357–64, for further discussion of this 'net'. R.S. Westfall first suggested a possible link between Newton's alchemical 'net' and the retiform particles he envisaged in the 'Conclusio' and other manuscripts in his biography of Newton. See Westfall, *Never at Rest*, op. cit. (71), p. 389.

[96] Newton, *Optice*, London: Royal Society, 1706, p. 339. I have quoted the English version, as it appeared later (and is insignificantly different from the Latin), in Query 31 of the 1717 edition of *Opticks*. I have used the New York: Dover, 1979 edn, pp. 395–6.

[97] For a discussion of the problem for the ancient Greeks see Wang, op. cit. (9), pp. 151–4.

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phenomena from which all else followed. Although Leibniz approved of Digby's 'absolute' account of it, perhaps impressed by its overtly metaphysical aspect, few others could overlook its outmoded Aristotelianism.

If condensation confronted the insurmountable problem of two bodies occupying the same space at the same time, explanations of rarefaction had to avoid assuming actions at a distance, which were regarded as equally impossible. In the case of rarefaction, however, the problem became even more pressing as a result of the extreme results achieved by Robert Hooke and Robert Boyle, using their newly invented air-pump. Their experimental achievements seem to have driven Newton, against all odds, to begin to think about the real possibility of actions at a distance. We know from the manuscript known as 'De Aere et Aethere' that repulsive forces came first in his thinking – as a way to explain the expansion of air into 'a thousand times its normal space, which would hardly seem to be possible if the particles of air were in mutual contact'. Newton immediately made an intellectual leap: 'but if by some principle acting at a distance [the particles] tend to recede mutually from each other …'

Attractive forces came next when he began work, shortly after, on the universal principle of gravitation, as triumphantly presented in the *Principia Mathematica*. It is evident, however, from the draft 'Conclusio' and the extended preface that he intended to include in the *Principia*, that he wanted to present there his new solution to the problem of rarefaction, although playing down the role of action at a distance, by talking of a net-like structure of matter – long rods of matter, still in contact with one another, with vacua in between. It was only in the 'Queries' he added to the *Optice* of 1706 and the second English edition of the *Opticks* in 1717 that he committed himself to the actions at a distance between particles that he had first envisioned in 1679, arguing in the 'Queries' about bodies taking up 'above a Million of Times more space than they did before'. There can be no denying that the problem of rarefaction had a profound effect on the historical development of physics.

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