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Aristotle's Theory of Chemical Reaction and Chemical Substances

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Abstract. The dominance of atomic structure in modern chemistry has led to an emphasis of the atomic tradition which overshadows what the subject owes to the other traditions. But there are definite features of modern chemical theory which hark back to one or other of the anti-atomistic conceptions. Aristotle maintained that the appearance of genuinely new substances, with properties radically different from the original constituents', could not be explained by the atomic theory. Some points of his critique of the atomists' theory of mixing could still be applied to 19th century atomism, and call for some care in discerning what general ideas have actually been retained from the atomic tradition. He argued that compounds are genuinely homogeneous—i.e. *every* part of any quantity of a compound is of the same kind as the whole—which led him to maintain that the constituents are not actually, but merely potentially, present in a compound. The theory is not without difficulties of its own. The present paper reviews the way Aristotle motivated his own approach and pursues the idea of constituents being potentially present in a compound.

1 Introduction

The aim of this paper is to formulate the Aristotelian idea that a substance is potentially, and not actually, present in a mixture or combination, and to consider some problems to which it gives rise.[1] This conception was adopted and adapted by Pierre Duhem (1902)

[1] Unfortunately, several English terms common to philosophers' discussions of Aristotle and everyday chemical idiom are not used in the same way. The word "substance" is understood throughout in the sense of chemical substance. Because I am obliged to follow English translations of Aristotle, however, "combination" and "compound" are used in the philosopher's sense—indicating a homogeneous mixture but without recognition of any distinction between solutions and compounds—for the sake of continuity with quoted passages.

as the basis his understanding of the diversity of chemical substances systematised by chemical formulas and for providing what he thought was the natural interpretation of matter as treated by thermodynamics. Aristotle's theory is pursued here from this Duhemian perspective, with an eye to its relation to contemporary macroscopic conceptions of chemical substance. Despite Duhem's many suggestions and allusions, however, questions remain which need to be resolved if the interpretation is to be at all definite.[2] Much the same might be said of Aristotle's own writings, and leading commentators have sought to fill out perceived lacunas with reconstructions which, as for example Freudenthal readily concedes, are "not explicit in Aristotle's writings" (1995, p. 200).

The aspects emphasised by Duhem suggest an approach somewhat different from Freudenthal's, not least in being, within a perspective of two and a half millennia, distinctly modern. This consciously anachronistic viewpoint may not be of interest to Aristotelian scholars, but may succeed in arousing interest on the part of those concerned with the roots of modern chemistry in an alternative to more familiar atomistic conceptions. The general approach of the theory focuses on what can still be regarded as the right problem, and the general lines of criticism of the atomists' approach to this problem could, in their essentials, be validly applied throughout the 19th century. One such line of criticism fixes on the idea of indivisibility, and was deflected only when atoms came to be treated as composed of several other entities. But this was by no means the only line of attack. The criticisms have been obscured by undue emphasis on the positivist objection entirely based on the premise that atoms couldn't be seen, which plays no role in the following discussion, just as it didn't for the interesting 19th-century opponents of atomism. The Aristotelian conception therefore has greater claim to be considered continuous with modern views than seems to be generally recognised, and a critical assessment of its merits illuminates the development of the modern macroscopic conception of substance. An exposition and analysis of Aristotle's theory of mixture from this perspective is developed in this paper.

2 Aristotle's Way of Setting up the Problem

In the course of spelling out the problem which the theory of substance should address, Aristotle considers various theories of his predecessors. The atomic theory of Leucippus and Democritus is singled out as of particular merit:

> Plato only investigated the conditions under which things come-to-be and pass-away; and he discussed not *all* coming-to-be, but only that of the elements. He asked no questions as to how flesh or bones, or any of the other similar things,

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[2] See Needham (2002a) for an interpretation of Duhem's view of mixtures.

> come-to-be; … In general, no one except Democritus has applied himself to any to these matters in a more than superficial way. Democritus, however, does seem not only to have thought about all the problems, but also to be distinguished from the outset by his method.

Whereas others fail to "give any account of combination … offering no explanation, e.g., of action and passion—how in natural actions one thing acts and the other undergoes action," Aristotle recognised that the atomists had a clear idea of how to deal with these issues:

> Democritus and Leucippus, however, postulate the 'figures', and make alteration and coming-to-be result from them. They explain coming-to-be and passing-away by their dissociation and association, but alteration by their grouping and position. And since they thought that the truth lay in the appearance, and the appearances are conflicting and infinitely many, they made the 'figures' infinite in number. (*DG* I.2, 315^a29-315^b11)[3]

Nevertheless, his critique is scalding. It might be considered to involve two strands, though intimately intertwined—that no coherent account is given of the ultimate atoms or "indivisibles," and that the theory fails to deal with the central problem, namely of explaining how new compounds, with new properties, can appear as a result of mixing. I will concentrate on the latter issue, of explaining the appearance and disappearance of substances, and remark on the former only in passing. In the light of Lewis's (1998) claims that the presocratic atomists didn't hold atoms to be indivisible, but merely undivided, it should be pointed out that Aristotle's case against atoms is by no means exhausted by arguments against the impossibility of separating their spatial parts. Even when the translation has him referring to atoms as indivisibles, indivisibility may not be at issue.[4]

On the atomic conception of combination, "constituents will only be combined relatively to perception; and the same thing will be combined to one percipient, if his sight is not sharp—while to the eye of Lynceus nothing will be combined" (*DG* I.10, 328^a13f.), so that substances only appear mixed to us because we cannot distinguish the individual juxtaposed particles. If the ingredients were thus preserved, combination would not be an objective physical state of matter, which Aristotle thought there was no

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[3] Quotations from Aristotle are taken from Barnes' edition unless otherwise indicated. *DG* abbreviates *On Generation and Corruption*, *Cael* abbreviates *On the Heavens* and *Meteor* abbreviates *Meteorology*.

[4] Lewis (1998, p. 2) says that whether the Greek adjective is to bear the modal (dispositional) construal or not is a matter of context, and therefore a matter of interpretation, rather than a feature that can be directly read off the word itself.

reason to accept. In fact, the atomic view has no real conception of chemical substances, but merely postulates shapes of atoms "infinite in number," as we saw, to account for "conflicting and infinitely many" appearances. Aristotle considers, on the contrary, that "there is a limit to the number of differences" (*Cael* III.4, 302^{b}31) exhibited by different substances, and an explanation of the variety of compounds must be based on a finite, and preferably small, number of properties. Democritus and Leucippus "have never explained in detail the shapes of the various elements … [and] the principles they assume are not limited in number, though such limitation would necessitate no other alteration in their theory" (*Cael* III.4, 303^{a}12-19). These primary properties, as they may be called, would explain how the mixing process can generate new substances, endowed with new properties, with the passing away of the properties of the original ingredients. No solution to "the paradox as to how flesh and bones and any other compounds will result from the elements," as one translator puts it, is to be found by conceiving of the process as mere "composition, just as a wall comes-to-be from bricks and stones …, [and that] this 'mixture' will consist of the elements preserved intact but placed side by side with one another in minute particles" (*DG* II.7, 334^{a}20-1, 334^{a}26f.; Forster's trans.). Rather, the mixing process would, by Aristotle's lights, involve the affecting of one piece of matter by another, and it is the primary properties which endow matter with the capacity to affect and be affected by other matter.

Aristotle's general views on the capacities and susceptibilities of matter are reflected in his difficulties in understanding the existence of atoms. For whereas the postulation of atoms was to explain the changes involved in mixing by different combinations of particles which persist unchanged, Aristotle couldn't see how they could be coherently described without ascribing to them properties which would prevent them persisting unchanged:

> it is impossible that they [the indivisibles] should not be affected by one another: the slightly hot indivisible, e.g., will suffer action from one which far exceeds it in heat. Again, if any indivisible is hard, there must also be one which is soft; but the soft derives its very name from the fact that it suffers a certain action—for soft is that which yields to pressure. (*DG* I.8, 326^{a}11-15)

Aristotle is posing a dilemma: either atoms are preserved intact, in which case no combination occurs, or combination occurs, in which case the atoms are not preserved intact. The notion of "combination" at issue here includes that of cohesion, but involves more than the mere sticking together of bits of matter; it includes the idea of the creation of a new *kind* of stuff, featuring properties not possessed by the original material. How could the mere juxtaposition of inert bodies generate new properties?

Since matter affects and is affected by matter in virtue of being of one kind of substance or another, questions arise of what indivisibles are made of and how that dictates their behaviour. One of Aristotle's difficulties with atoms stems from this idea that they must be made of some substance and his rejection of the idea that a single substance is naturally separated, like a heterogeneous mixture of oil and water which are two substances. Pieces of the same kind of matter would form a uniform whole, as do drops of water when they come into contact: "if all of them [the indivisibles] are uniform in nature, what is it that separated one from another? Or why, when they come into contact, do they not coalesce into one, as drops of water run together when drop touches drop …?" (*DG* I.8, 326^{a}31-3). Yet if they were made of different kinds of stuff, comprising a heterogeneous mixture, they would evidently be divided (and not merely divisible) into separate parts. They must be uniform. But then, why should uniformly constituted bodies divide into particles of one size and not another? As Aristotle puts it, "why should indivisibility *as such* be the property of small, rather than of large, bodies?" (*DG* I.8, 326^{a}23f.).

Aristotle simply takes the view that some quantities of matter are uniform or homogeneous, whereas others are heterogeneous mixtures, exhibiting a natural separation into homogeneous parts. The uniformity implied by homogeneity seems to be taken as an indication of a single substance, and compounds resulting from mixing are required to be homogeneous, just like the elements themselves:

> if combination has taken place, the compound *must* be uniform—any part of such a compound is the same as the whole, just as any part of water is water (*DG* I.10, 328^{a}10f.),

where again water is taken as a paradigm. Passages such as these clearly express the view that single substances are homogeneous, or as Aristotle says, homoeomerous (literally, whose parts are like the whole). This is borne out by what he says in favour of rejecting the natural separability of a single substance. What would now be understood as a heterogeneous, two-phase mixture of a single substance—of ice and liquid water, say—all of whose parts are not like one another, is foreign to the Aristotelian view. Different phases were understood, it seems, to comprise different substances, so that a single substance constitutes a single phase. Moreover, the general tenor of his argument certainly suggests that he subscribed to the converse thesis—that homogeneous quantities comprise a single substance. He says, for example, that anyone who adopts "the view of Anaxagoras that all the homoeomerous bodies are elements … misapprehends the meaning of element. Observation shows that even mixed bodies are often divisible into homoeomerous parts; examples are flesh, bone, wood, and stone" (*Cael* III.4, 302^{b}13-7). The fact that Aristotle takes it that there obviously is a problem of explaining the variety of compounds presupposes that different substances can be easily recognised as such, and the homogeneity criterion of sameness of substance would provide such a means.

The distinction between homogeneous and heterogeneous matter derives from observable features of what would now be called macroscopic phenomena. But it would be wrong to understand Aristotle as dismissing atomism on the grounds that the ultimate inhomogeneity it ascribes to mixtures is not directly observable. Aristotle's respect for observation didn't preclude theoretical treatment. But he saw nothing that would count in favour of the atomist view which would justify contravening the apparent homogeneity of bodies, and much that counts against it. He devised his own approach as the only way of accommodating and explaining what could be observed. Later, the Stoics came to see an opening for a third general view, but this required denying a thesis common to both the atomist and Aristotelian conceptions of the impenetrability of matter—a denial which many philosophers have balked at since. In any case it is questionable, although this can't be argued here, to what extent they succeed in putting Aristotle's position aside.[5]

3. The Aristotelian Theory of Mixing

The requirements of the Aristotelian conception of mixing, which play a major role, we saw, in his criticism of the atomic theory in *DG* I.8, are first laid out in *DG* I.6. The new properties of mixts arise from the interplay of contraries when the bodies that bear them come into contact. Contrary properties capable of endowing matter with the ability to act and the susceptibility to be acted upon are thus restricted to tangible properties—those which act by virtue of spatial contact of the bodies which bear them. In *DG* II.2 it is argued that these contraries can be reduced to two pairs—moist and dry, hot and cold—from which other tangible contraries, such as solidity and fluidity, can be derived, but which are not themselves further reducible to one another.

Chemists have continued in considerably more recent times to base their explanations of the transformations of substances on the interplay of contraries. Acids are contrasted with bases, electropositive with electronegative substances, and so on. But by modern lights the range of properties Aristotle thought it adequate to consider is restricted, to say the least; and even within the confines of this range, the arguments for the reduction to the four primary qualities of fundamental phase properties and suchlike are, where comprehensible, unconvincing. Even from within Aristotle's purview, the status, within this scheme of reduction, of lightness and heaviness exhibited by the natural motions of the elements as they move to different parts of the sublunar region, remains something of a mystery. Nevertheless, the general strategy should be clear enough. A body is warmed when it comes into contact with a hot body, provided the former is cold, or at least less hot; and a moist body wets another when in contact. The

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5 For a discussion, see Needham 2002a.

primary qualities endow matter with the capacity of acting and being acted upon—the "action" and "passion" in virtue of which something happens on mixing, involving the disappearance of old substances and the appearance of new.

The broad strokes of Aristotle's theory of mixing must strike the modern chemist as remarkably familiar. General considerations of stability determine whether reaction is possible at all; and where possible, separate considerations are relevant to the circumstances determining the rate of reaction. As for the general "thermodynamics,"

> Amongst those things … which are both active and passive, some are easily divisible. Now if a great quantity (or a large bulk) of one of these materials be brought together with a little (or with a small piece) of another, the effect produced is not combination, but increase of the dominant; for the other material is transformed into the dominant. (That is why a drop of wine does not combine with ten thousand gallons of water; for its form is dissolved, and it is changed so as to merge in the total volume of water.) On the other hand, when there is a certain equilibrium between their powers, then each of them changes out of its own nature towards the dominant; yet neither becomes the other, but both become an intermediate with properties common to both. (*DG* I.10, 328^{a}24-30)

Immediately following this passage, Aristotle points out that such circumstances are not sufficient to determine the "kinetics" of mixing:

> Thus it is clear that only those agents are combinable which involve a contrariety—for these are such as to suffer action reciprocally. And further, they combine more freely if small pieces of each of them are juxtaposed. For in that condition they change one another more easily and more quickly; whereas this effect takes a long time when agent and patient are present in bulk. (*DG* I.10, 328^{a}31-5)

Two kinds of interaction between substances are distinguished in the former passage. The first strikes modern readers as distinctly odd, and they will search Aristotle's texts in vain for an answer to the question immediately arising of exactly when a difference in bulk is just sufficient to tip the balance from combination to the overwhelming, as Aristotle sometimes says, of the less abundant ingredient by the other. Even the notion of the relative amounts of material, and the property whose magnitude provides the measure of this relative amount, is, as we will see, deeply unclear. But here it seems that "bulk" means volume, in which case we can ask how the existence of processes of this first kind squares with the initial claim that contact is a prerequisite for all interactions. Two bodies come into contact, it would seem, at their common surface. A common surface is the same for both bodies, however, whatever the ratio of their volumes. Accordingly, if exceeding a certain difference in (or ratio of?) volume is necessary and (in the absence of hindrance) sufficient for a certain kind of interaction, and for precluding effects of another kind of interaction, then the contact condition cannot be taken quite literally. This seems to be Aristotle's view, since he does loosen up the contact condition.

The important point introduced by the contact condition is that "contact *in the proper sense* applies only to things which have position" (*DG* I.6, 322^{b}32f.), and the imposition of the property of occupying a region of space precludes, for example, numbers exerting any influence. (Aristotle thought that the atomist conception of Leucippus and Democritus "in a sense makes things out to be numbers or composed of numbers. The exposition is not clear, but this is its real meaning" (*Cael* III.4, 303^{a}9f.).) Although Aristotle goes on immediately to say that touching is "defined" as having extremities together, it soon transpires that he doesn't hold himself to this definition at all. Rather, touching "in general applies to things which, having position, are such that one is able to impart motion and the other to be moved" (323^{a}23f.). Had he strictly adhered to the original definition, it would follow that touching is a symmetric relation. But he allows that, although "[a]s a rule, no doubt, if A touches B, B touches A …Yet it is possible … for the mover to merely touch the moved, and that which touches need not touch a thing which touches it" (323^{a}25ff.). So touching has become a general relation of affecting, and possibly occasioning being affected, standing between objects which occupy positions in space and, perhaps, are not too far apart. The passage just quoted raises the possibility of touching without being touched, which may be interpreted as a statement of Aristotle's general thesis that all changes can be traced to an unmoved mover. (Gill 1989, pp. 199ff.) gives the example of the art of medicine, "located" in the soul of the doctor, touching the sick patient without itself being touched.) But interactions of the first kind, in which one body overwhelms another, would seem to be cases of touching without being touched. For in overwhelming another, a body is not itself affected by its action like one which combines with another body by a process of the second kind described in the passage from *On Generation and Corruption* I.10 above.

Combination entails a mutual affection in which the primary qualities are affected in both interacting bodies. As the idea is more succinctly summarised later,

> flesh and bones and the like come-to-be when the hot is becoming cold and the cold becoming hot and they reach the mean, for at that point there is neither hot nor cold. … In like manner also it is in virtue of being in a "mean" condition that the dry and the moist and the like produce flesh and bone and the other compounds. (*DG* II.7, 334^{b}25ff.; Forster's trans.)

When the relation of the bulks of the two quantities of matter is below the threshold for overwhelming, the aggregated powers endowed by the primary qualities strive towards a mean, intermediate between the original values. Opposing contraries correspond to different degrees on a single scale. Hot and cold, for example, are two extremes of the same magnitude, let us call it warmth, and moist and dry two extremes of humidity. In modern terms, the primary notions are basically relational, things not as warm as one another being distinguished in virtue of the one being warmer than, or conversely, colder than, the other, and the other primary notion of humidity can be similarly understood in terms of a relation "is at least as humid as." Not only does what is hot, or supremely warm, affect what is minimally warm, or cold; it is in general possible that "the slightly hot …, e.g., will suffer action from [that] which far exceeds it in heat" (*DG* I.8, 326^{a}12f.), or indeed whatever has some degree of a primary quality by whatever has a different degree. Thus, any two bodies of the same order of size, the one warmer than the other, can combine in a mixing process of the second kind to generate yet a further degree of warmth, intermediate between the original two and therefore different from both. This seems to be Aristotle's conception of the new properties resulting from combination.

An important corollary now follows from these considerations. The compounds generated by such mixing processes are homogeneous in the sense explained above: "if combination has taken place, the compound *must* be uniform—any part of such a compound is the same as the whole, just as any part of water is water." Homogeneity also applies to the original ingredients. (If not, on the supposition introduced above, the ingredient will be a heterogeneous mixture, comprising homogeneous parts which are single substances.) Consequently, *each part* of the resulting compound will display a new property—reducible, on Aristotle's view, to new degrees on the scales of warmth and humidity. No part will exhibit any of the original properties, and therefore none of the original substances is preserved in the compound. They have all passed away.

Although this important corollary of Aristotle's theory is an inevitable consequence of the homogeneity requirement, it is not dependent on that requirement. Combination, according to Aristotle, is a process arising from the interaction of bodies in virtue of their powers and susceptibilities to affect and be affected by one another. It is precisely the properties conferring these powers and susceptibilities which are characteristic of the initial ingredients, and the changes wrought by mixing ensure that the properties initially characterising quantities of matter as one kind of substance or another no longer obtain, and are replaced by others characterising a different substance. His charge against the atomists, we saw, was that even the small particles they envisage must be made of some substance, in virtue of which they will be susceptible to modification and thus not survive intact in the creation of new substances. Such changes might conceivably be incorporated into a theory which doesn't require the products of mixing to be strictly homogeneous.

This corollary is a central pillar of Aristotle's theory, and a fundamental bone of contention on competing theories. He prepares for it in the lead up to the two-fold theory of mixing by introducing his famous distinction between actual and potential:

> Since, however, some things *are potentially* while others *are actually*, the constituents can be in a sense and yet not-be. The compound may *be actually* other than the constituents from which it has resulted; nevertheless each of them may still *be potentially* what it was before they were combined, and both of them may survive undestroyed. (*DG* I.10, 327^{b}23ff.)

So the original ingredients "may survive" in so far as they *can* be recovered from the compound. This is sharply distinguished from separability of ingredients as envisaged by the atomists: "re-separation … differs from reconstitution in implying that in some way the ingredients are there all along" (Sorabji 1988, p. 67). Something has to bear the property of being possibly of one or other of the original substance kinds, and this is the material of the compound which, as he says, "can be" of the original constituent kinds yet (actually) is not. This is not the ludicrous claim that the matter of the compound doesn't have these original kind properties (corollary above) and yet does. It is the claim that this matter doesn't have these properties but could have. The precise formulation of this modal feature calls for more attention, however, and is taken up again in §7 below.

4. Aristotle's Conception of Elements

The second book of *On Generation and Corruption* gets under way with the reminder that "we have still to consider the elements" (*DG* II.1, 328^{b}32). This notion has not played any role in Aristotle's development of the general conditions governing the coming-to-be and passing-away of substances in the first book. In particular, combination was not introduced as a matter of simple bodies coming together to form complex bodies, but of bodies endowed with the potential to act and the susceptibility to be acted upon coming together and realising their potential. The elements are eventually defined in II.3, after certain preliminaries have been dealt with.

The preliminaries establish the general pattern to which the definitions of the elements are to conform. To begin with,

> Our own doctrine is that although there is a matter of the perceptible bodies (a matter out of which the so-called elements come-to-be), it has no separate existence, but is always bound up with a contrariety. (*DG* II.1, 329^{a}24f.)

Aristotle goes on say that matter "underlies, though it is inseparable from, the contrary qualities; for the hot is not matter for the cold nor the cold for the hot, but the *substratum* is matter for them both" (329^{a}30f.). Scholars are divided about whether the passage from which these quotations are taken commits Aristotle to a doctrine of prime matter or not. I confine myself to the observation that Aristotle is saying that what has to be defined are properties—the properties of being such-and-such a kind of element for the various elemental substances—in terms of other properties, and this in turn imposes certain constraints. Properties have to be predicated of something—the subject that bears them, or as he says, underlies them, or is a substratum for them. There is no question of isolating the underlying matter in the sense of entirely "separating" it from the properties it bears. At any particular time, then, a quantity of matter can be designated as that which bears such-and-such a property at that time—that which is hot, for example, or the hot for short. This doesn't entail that the properties borne by matter are necessary features of the matter; properties may be acquired and relinquished. But at no time is matter entirely devoid of properties. The elemental properties, in particular, are transient. Aristotle subscribed to a doctrine of the transmutability of the elements, and the matter of the recently destroyed element is that "out of which" the new one comes-to-be. In principle, all the properties (of a certain group) possessed by a quantity of matter might conceivably change simultaneously without there ever being a time when no property applies. But Aristotle seems to impose restrictions. Elements at least cannot all undergo transmutation by modifying all their element-characterising properties at once, and some must remain unchanged while the others are modified. But under no circumstances could the hotness of a body, say, be preserved at the same time as it is modified into its contrary. During a process in which the warmth of a body is decreased, there must be something bearing each of the different degrees of warmth. And although such changes might be loosely described by saying that the properties of bodies may be changed, it is "bodies [that] change into one another …, whereas the contrarieties do not change" (329^{b}1f.). Change is change in matter involving the gaining of properties it lacks; properties are not what change.

"Matter" will be used here to refer to the bearer of substance properties such as the elemental ones, with no implication of the features sometimes ascribed to the so-called prime matter, such as imperceptibility and pure potentiality. Matter is observable unless of microscopic dimensions, and endowed with potentialities in virtue of the properties it bears.

As for the properties in terms of which the elemental properties are to be defined, Aristotle assumes they are to be taken from contraries, and goes on to ask "What sorts of contrarieties, and how many of them, are to be accounted principles of body? … other thinkers assume … them without explaining why they are *these* or why they are just *so many*" (329^{b}3f.).

Aristotle seeks the explanation for the particular defining properties of the elements in some distinctive feature of what generally explains coming-to-be and passing-away by enabling them to enter into one of the two kinds of reaction described in I.10. As with any substance capable of entering into reaction, he claims in II.2 that "the elements must be reciprocally active and susceptible, since they combine and are transformed into one another" (329^{b}23f.). Moreover, "hot and cold, and dry and moist, are terms, of which the first pair implies *power to act* and the second pair *susceptibility*" (329^{b}24f.). Aristotle goes on to argue that other relevant features are all derived from warmth and humidity, "but that these admit of no further reduction. For the hot is not *essentially* moist or dry, nor the moist *essentially* hot or cold; nor are the cold and the dry derivative forms, either of one another or of the hot and the moist. Hence these must be four" (330^{b}25ff.). Thus, other relevant features are reduced to warmth and humidity, and the distinctive feature of elemental properties is that they are defined in terms of what he later calls "contrary extremes" (*DG* II.8, 335^{a}8) of warmth and humidity—what is hot is what is as warm as can be, and so forth. This explains, then, why the principles are four in number.

Substances in general are to be characterised by properties conferring an active power to affect others and a passive susceptibility to be affected, and these are derivable, according to Aristotle, from degrees of the primary qualities, warmth and humidity. Four special cases are the extreme values of these primary determinables: maximal and minimal degrees of warmth—hot and cold—and of humidity—moist and dry—presumably conferring particularly potent powers and susceptibilities. The extreme degrees are, at any rate, what distinguish the elements as Aristotle defines them in II.3. Of these,

> any four terms can be combined in six couples. Contraries, however, refuse to be coupled; for it is impossible for the same thing to be hot and cold, or moist an dry. Hence it is evident that the couplings of the elements will be four: hot with dry and most with hot, and again cold with dry and cold with moist. (*DG* II.3, 330^{a}30ff.)

So there will be exactly four elements, the pairs corresponding, respectively, to fire, air, water and earth.

Aristotle goes on immediately to speak of the elements as simple, and in so doing appeals to a generally accepted idea on the part of "all who make the simple bodies elements" (330^{b}7). Just as he questioned whether his predecessors had any explanation to offer of the characterisations they offered of elements, so he might have raised some questions about their conception of simplicity. But surprisingly enough he doesn't do so in *On Generation and Corruption*, where he goes on to speak of the elements as simple despite the fact that the manner of defining them just presented makes no appeal to any such notion. This must strike the contemporary reader as rather strange. When Lavoisier introduced the modern notion of an element as the "last point which analysis is capable of reaching," he stressed that there can be no further restrictions on the number and character of the elements; "we must admit, as elements, all the substances into which we are capable, by any means, to reduce bodies by decomposition" (1789, p. xxiv). He criticised the Aristotelian doctrine of the four elements accordingly. If we adopt the one procedure—of defining the elements as what cannot be further decomposed, or of defining them of the basis of other considerations such as the possession of extreme contraries as Aristotle does in *On Generation and Corruption*—then we can't, it seems, reasonably adopt the other. Not that to do otherwise necessarily involves a contradiction; but it should be an open question whether what satisfies the condition imposed by one definition also satisfies the other, and not something that can be decided a priori. Nevertheless, Aristotle does precisely that, actually proposing a definition of the general idea of an element in a manner akin to Lavoisier's definition in another work, *On the Heavens*. The Aristotelian notion of simplicity is deeply problematic, however. The issue is taken up in §6 below.

This is not the only point of conflict with the Lavoisian conception. Having defined the elements, Aristotle goes on immediately to ascribe them a feature which radically distinguishes them from what Lavoisier understood as an element. The theme of the next chapter is introduced with the claim that "it is evident that all of them are by nature such as to change into one another" (*DG* II.4, 331^{a}13), and Aristotle takes it upon himself to "explain what is the manner of their reciprocal transformation, and whether every one of them can come-to-be out of every one" (331^{a}11f.). Bodies with contrary properties will naturally affect one another, and Aristotle quickly turns to considerations bearing on the rate of change:

> it is easier for a single thing to change than for many. Air, e.g., will result from Fire if a single quality changes; for Fire, as we saw, is hot and dry while Air is hot and moist, so that there will be Air if the dry be overcome by the moist. Again, Water will result from Air if the hot be overcome by the cold; … (*DG* II.4, 331^{a}25-30)

In general, any element can change into another with a defining feature in common. Any element can, in fact, be transmuted into any other. But

> the transformation of Fire into Water and of Air into Earth, and again of Water and Earth into Fire and Air, though possible, is more difficult because it involves the change of more qualities. For if Fire is to result from Water, both the cold and the moist must pass-away; … This second method of coming-to-be, then, takes a longer time. (*DG* II.4, 331^{b}4-11)

Gill suggests that transmutations of the latter kind are slower because continuity requires that the two contraries at issue must change consecutively and not simultaneously: "the dryness of fire can first be overpowered to yield an interim air, and then the heat can be overpowered finally to yield water; alternatively, the heat of the fire can first be overpowered to yield an interim earth …" (1989, p. 74). Rather than requiring that all interim stuff be elemental, the idea of continuity might equally be thought to require successive change through all intermediate degrees. A quantity of water, say, would then be changed to air by all of the quantity successively passing through all intermediate degrees of warmth, so no part of this quantity is of either element kind within the transition period. Which of the two kinds of transformation process distinguished in I.10 is involved in transmutation is settled by these passages from II.4, however. Transmutation is a process of the first kind, in which one piece of matter of a given kind is sufficiently larger in size than the other piece of matter of another kind that the primary qualities of the former overwhelm those of the other, and no intermediate degree is realised. (In I.10 it seems that the conjunction of properties constituting a substance kind, elemental or not, simultaneously overwhelm; but in II.4 it is the overwhelming of extremes of warmth and humidity one at a time that is at issue.) It is not clear how such a discontinuous transformation could be anything but instantaneous if there are no intermediate stages to be traversed. But this also seems to say something about particle size, which we saw in the last section is a factor governing the rate of transformation. Aristotle says, for example, that "if water has first been dissociated into smallish drops, air comes-to-be out of it more quickly; while, if drops of water have first been associated, air comes-to-be more slowly" (*DG* I.2, 317^{a}27-30). Perhaps certain parts of the overwhelming quantity which are sufficiently larger than particular parts of the overwhelmed quantity and in sufficiently close contact with these parts overwhelm first. Then other parts can come into suitable position and overwhelm, so that the entire transformation does take place in a temporally ordered sequence of stages. On this acount it is the division of quantities which explains the rate of transformation. But if the process proceeds by stages, why can't the quantity converted to an interim element in the first stage be transformed into the final element at the same time as the second stage of transformation of another part to the interim element is under way, and so on? In that case, transformations of fire to water and air into earth need hardly be much slower that other elemental transmutations.

It is not clear to me that a choice can be made between alternatives such as these on the basis of Aristotle's texts, or that it is possible to see on what Aristotle based his various claims about differing rates of transformation in *DG* II.4. Nevertheless, strange as all this may seem to us, Aristotle took himself to be addressing an "evident" phenomenon seen in everyday occurrences. The conversion of water to air is how Aristotle conceives of evaporation, which according to his theory proceeds more quickly than the conversion of water to fire when exposed to an excess of the latter; solidification involves the coming-to-be of earth; combustion the conversion of earth to fire, which is again quicker than conversion of water to fire.

On the post-Lavoisian conception, elements are usually understood to be preserved during chemical transformation. But the general corollary of the last section implies that, on Aristotle's theory, when elements combine to form compounds by a mixing process of the second kind, they are not preserved in the resulting compound. And now we have seen that they are susceptible to another kind of transformation, transmuting into other elements as a result of a mixing process of the first kind. Elements are as ephemeral as any other kind of substance on the Aristotelian view. Whatever might be said about this doctrine, it should not be confused with the denial of the persistence of matter. Although the ideas of preservation of elemental kinds and the persistence of matter are intimately associated on the post-Lavoisian view, Aristotle has made ample provision for distinguishing these ideas, and so cannot be criticised for incoherently denying persistence on the grounds of denying preservation of the elements. This is central to the present interpretation and worth spelling out properly.

When water becomes air, for example, that which was the water, and so was cold and moist, *is identical with* that which is later air, and so hot and moist. The primary qualities hot, cold, moist and dry are therefore properties which may apply at one time, t, and not at another, t', to pieces, or following usage in the discussion of the logic of mass terms, quantities,[6] of matter π, ρ, σ, …. The primitive relations of warmth and humidity in terms of which the extreme contraries are defined are, accordingly, also to be understood as time-dependent relations, π being as warm as ρ, for example, at a time t.[7] Thus, defining water is a matter of defining a property by:

π is water at t if, and only if, π is cold at t and π is moist at t,

and air by

π is air at t if, and only if, π is hot at t and π is moist at t,

and so on. A transmutation from water into air will, accordingly, involve the truth of a conjunction of the kind "π is water at t & π is air at t'," where t' is later than t but the same object, π, bears the different properties.

5. A Textual Problem

Persistence of matter, thus interpreted in terms of the identity of what undergoes change, is arguably what is at issue in the passages van Brakel (1997, p. 258 and fn. 14) cites in support of his claim that the general view since Aristotle has been that "[w]ater in all its modifications (liquid, solid, vapour) is the same substance." With one exception (from *Problems*), all the several passages van Brakel mentions are taken from

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6 See, e.g., Cartwright (1970) and Roeper (1985).

7 It might be suggested that they should in fact be indexed with two times in order to accommodate statements of the kind "π is now warmer than ρ was." But such details are not pursued here.

Meteorology. The one he actually quotes most clearly seems to conflict with the conception of the transmutation of the elements described above: "the finest and sweetest water each day … dissolve[s] into vapour and rise[s] into the upper region, where it is condensed by the cold and falls again to the earth." But placing the passage in context shows that Aristotle thinks of the change as involving generation and destruction:

> the sun … by its movement causes change, generation and destruction—it draws up the finest and sweetest water each day and makes it dissolve into vapour and rise into the upper region, where it is condensed by the cold and falls again to the earth. (*Meteor*. II.2, 354^{b}6ff.; Lee's translation)

The "it" in "makes it dissolve into vapour" is naturally taken to refer to that *thing* which is "finest and sweetest water," and this doesn't necessarily entail preservation of the *property* of being water. It is this thing which loses these properties and becomes vapour. That he speaks of this thing dissolving fits with what has been said about the mechanism of transmutation involving a mixing process of the first kind.[8] More generally, Aristotle argues that "[e]ternal they [the elements] cannot be, for both fire and water and indeed each of the simple bodies are observed in process of dissolution" (*Cael* III.6, 304^{b}26f.). The issue is not quite so cut and dried, however, and draws attention to some of the tensions which arise in comparing Aristotle's various texts.

Van Brakel could respond by pointing out that two chapters later Aristotle says what he means by vapour, namely that "vapour … is moist and cold" (360^{a}22f.), i.e. has the defining features of water. Once again, however, the picture is tainted by the larger context. Air in *Meteorology* is not the simple element described in *On Generation and Corruption*, but a mixture of vapour and smoke. The latter substance is called upon because "it is absurd to suppose that the air which surrounds us becomes wind simply by being in motion" (*Meteor*. II.4, 360^{a}26f.; Lee's trans.). The details of Aristotle's theory of the winds need not be pursued here. Even in *On Generation and Corruption*, however, there is an unelaborated comment in II.3, where the definitions of the four elements are given, hinting at further restrictions on the number of elements—"Fire and Earth … are extremes and purest; Water and Air, on the contrary, are intermediates and more combined" (II.3, 330^{b}34f.)—although this puts water and air on a par as far as their elemental status is concerned. As it stands, however, this might just be a badly formulated way of saying that what actually occupies the intermediate region between the centre occupied by earth and the upper region occupied by fire is not in fact water and air, but mixtures which are less watery (like water) or airy than the matter below is

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[8] The translator points out that Aristotle usually makes no distinction between dissolution and melting (*Meteor*. p. 318, fn. a; Lee's trans.).

earthy and the matter above fiery. But *Meteorology* definitely goes a step further. There it is maintained that

> Air … is made up of these two components, vapour which is moist and cold … and smoke which is hot and dry; so that air, being composed, as it were, of complementary factors, is moist and hot. (*Meteor.* II.4, 360^{a}21ff.; Lee's trans.)

Why in particular the two of the contraries cold and dry should be annulled, and not the other pair, remains unexplained, however. It would also seem that the theory of winds requires that the air is not homogeneous, and the two components form a juxtaposition rather than a compound. The annulment of contraries just mentioned would not be a local phenomenon, then, holding of every part of the air, but a large-scale phenomenon, noticeable only to someone unable to discern the distinctly qualified parts. This doctrine seems radically different from the theory developed in *On Generation and Corruption*. And in *On the Heavens* III.7, in the course of arguing against the atomist conception, Aristotle actually disputes the thesis that "water is a body present in air and excreted from air" by arguing that "air becomes heavier when it turns into water" (305^{b}9f.). Any suggestion that the air of *On Generation and Corruption* and *On the Heavens* is a theoretical notion, as against the observable substance treated in *Meteorology,* must reckon with the frequent appeal to observation to dismiss alternative views in the former two works, such as that at *Cael* IV.5, 312^{b}34ff. and passages discussed in connection with this topic above.

Meteorology is a study of the phenomena which occur in the sublunar region—of "everything which happens naturally, but with a regularity less than that of the primary element [translator's fn.: The fifth element of which the heavenly bodies and their spheres are made] of material things" (*Meteor.* I.1, 338^{b}20f.; Lee's trans.). It is clearly conceived at the outset as building on the general theory of matter and change laid down in *Physics* and *On Generation and Corruption*. But it seems that in striving to accommodate these phenomena, Aristotle has stretched his original theory beyond the limits of consistency. So it is doubtful that whatever counts in favour of regarding water as preserving its waterhood when changing to air in *Meteorology* can be treated as a straightforward elaboration of the doctrines of *On Generation and Corruption* and *On the Heavens*. There are divergences in the latter two works too, to which we now turn; but these are more easily regarded as complementing one another.

6. Simple substances

Following the development of Aristotle's ideas in *On Generation and Corruption*, the notion of an element has been characterised in terms of properties determining how substances react with one another to generate new substances. According to the Aristotelian conception, such properties are realised in varying degrees, and can all be reduced to two primary magnitudes. The elements distinguish themselves by taking on extreme or limiting values of these underlying determinables. Otherwise, they share with all other substances capable of entering into mixing processes or reactions the feature that they are not present in a compound, so that no part of a compound bears the element-defining characteristics. Thus, the elements are characterised by features exhibited only in isolation. Other theories of the elements might treat them as more widespread, but for Aristotle something is an element only when in isolation. Another notion Aristotle associates with the idea of an element, that of simplicity, has been mentioned without being integrated into the account. It is now time to consider how this might be done.

Simplicity is normally taken to be a feature distinguishing elements from other substances in virtue of an idea of composition—simple substances are those which are not composed of any other substances. Is such a notion available to Aristotle given what his theory already commits him to as summarised in the previous paragraph? It might seem that the idea is only available on theories like those of the atomists and the Stoics, which have it that the original components are preserved even in the most intimate of mixtures. Since the original ingredients are not present in a compound on Aristotle's conception, it might seem that he is not in a position to talk of components of a compound, and so not in a position to distinguish between simple and complex substances by contrasting substances composed or not of other substances.

Aristotle clearly didn't agree. He goes so far as to declare that "every compound will include all the simples bodies" (*DG* II.8, 335^{a}9). This immediately raises the further question of what, if all compounds are alike in being compounds of all four elements, distinguishes one particular compound from another. They are distinguished by their different degrees of warmth and humidity on the conception of mixing developed in *On Generation and Corruption*, and these features should be paralleled by some difference in constitution if this new idea is to be upheld. In I.10 Aristotle contrasts a compound with an inhomogeneous juxtaposition, whose parts do not "exhibit the same ratio between its constituents as the whole" (328^{a}9), suggesting that proportions of component elements can be distinguished and are characteristic of particular kinds of compound. The statement from II.8 occurs towards the end of *On Generation and Corruption*, where Aristotle summarises his theory without—the fleeting reference to ratios in I.10 notwithstanding—carefully introducing the new idea into his scheme as he had done with other aspects of his theory. Is it even compatible with the rest of the theory? Clearly, the notion of composition at issue cannot be that of actually comprising various substances as parts, which is precluded by the corollary discussed in §3. It must involve the notion of potentiality. A component must be a substance that can be obtained from a compound. But there must be more to it than that since the elements do not distinguish themselves from compounds in respect of disposition to become other substances. Any substance can enter into a mixing process (of the first or second kind) and be entirely converted into another; elements are no exception.

In Aristotle's discussion of the elements in *On the Heavens*, the leading idea is precisely the distinction between simple and complex, rather than what governs mixing processes as in *On Generation and Corruption*. "An element, we take it, is a body into which other bodies may be analysed, present in them potentially or in actuality (which of these is still disputable), and not itself divisible into bodies different in form. That, or something like it, is what all men in every case mean by element" (*Cael* III.3, 302ª15ff.). This is not the way the notion of an element was introduced in *On Generation and Corruption*. Nevertheless, given the reference there to simple bodies, and the reference here to all men, but more importantly, to potential presence, it is presumably thought to be consistent with it. The problem at the end of the last paragraph is addressed in *On the Heavens* with the claim that "flesh and wood and all other similar bodies contain potentially fire and earth, since one sees these elements exuded from them; and, on the other hand, neither in potentiality nor in actuality does fire contain flesh or wood, or it would exude them" (*Cael* III.3, 302ª20ff.). Presumably the idea is that a quantity of pure flesh can be converted into a quantity which is part fire, part earth, these parts occupying spatially separated regions. Starting with a quantity of fire, on the other hand, and *without the addition of any other matter*, it is not possible to obtain flesh or wood. A quantity of fire can be converted into flesh and wood, just as Gill points out that "earth is potentially clay and potentially wood" (1989, p. 150), but only by mixing with some other quantity of matter. For the fact remains that on the Aristotelian conception, what is flesh and wood can become fire and earth, and what is fire and earth can become flesh and wood. It seems, however, that the theory of mixing is to be interpreted to say that conversion of one kind of substance to another is only possible by a *mixing* process (whether of the first or the second kind). At all events, to the extent that it is unclear whether Aristotle has a notion of a physical process of heating which is not a mixing process of the first or second kind, we should be wary of reading our notion of decomposition by heating into his theory. In that case, failure of the parts of a quantity of some kind to be converted to any other without the addition of any other quantity of matter hardly distinguishes the elements, and the burden of explaining the Aristotelian notion of components rests heavily on the idea of a ratio of components. But without Lavoisier's use of the notion of mass to keep track of the amounts of different elements constituting a quantity of a compound, the practical implications of this idea are not easy to see. Of course, none of the views which Aristotle opposed were any better in this respect.

Practical matters aside, Aristotle's theoretical conception of components might be pictured along the following lines. A quantity which is a compound of a given kind is a homogeneous body with specific degrees of warmth and humidity lying between the extreme values found for these magnitudes. A compound kind has a characteristic degree of warmth, *w,* and degree of humidity, *h*, and can be denoted by a pair (*w*, *h*), any quantity of which is represented by a point O in Fig. 1 below. A body of this kind might have resulted from a mixing process of the second kind involving initial ingredients of kinds (w', h') and (w'', h''), represented by points O′ and O″, respectively. The degree *w* is intermediate between w' and w'', and *h* between h' and h'', presumably[9] in relation to how much of each of the initial kinds of substance were mixed. How, exactly, this is determined—indeed, what the measurable quality is in respect of which the amount of each quantity might be described—is not specified in Aristotle's texts, and we can only guess at what, if anything, he had in mind. But let us consider how the problem might be approached within the Aristotelian framework.

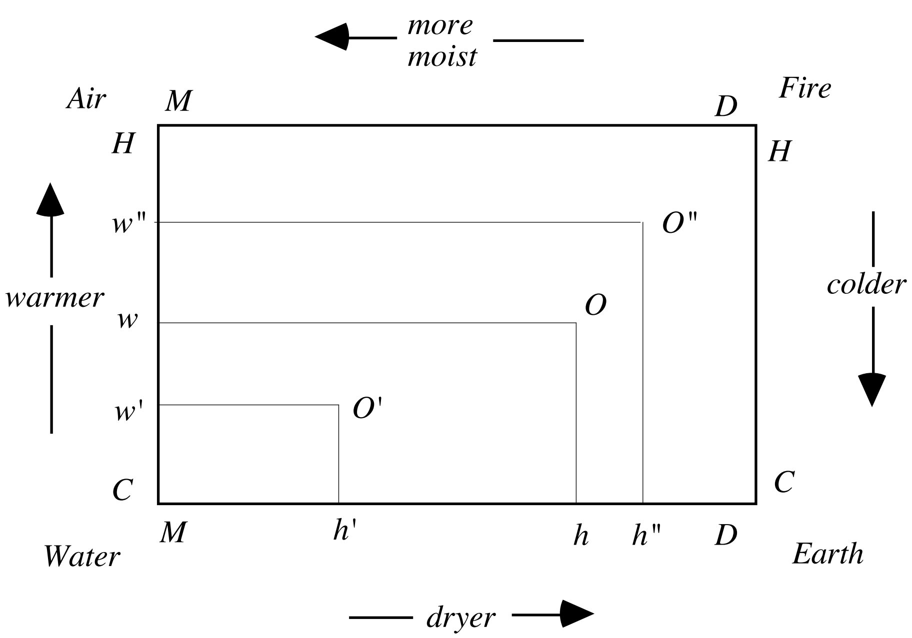

Fig. 1

Perhaps the original ingredients can be recovered from the quantity of kind (*w*, *h*). But there is no reason to suppose that only one kind of conversion into different substances is possible. This is the case with the modern view of compounds, which might be decomposed into different sets of compounds in different ways, and it is only

9 by analogy with the "method of mixtures" in calorimetry.

decomposition entirely into elements that is unique. So too, Aristotle's idea seems to be that any compound can be split entirely into substances bearing extreme degrees of the primary magnitudes, i.e. the elements, represented by the corners of the diagram. But is there any reason, even in this case, to think that the analysis would be unique? Suppose mixing water with earth in certain proportions yields a quantity with degree of humidity *h*. Further addition of air might bring it to degree of warmth *w*. But this same combination of degrees of warmth and humidity might also be realised by taking less air and some fire, together with less than the original amount of earth to compensate for the extra dryness introduced by the fire. In short, two independent variables *w* and *h* are insufficient to determine three independent ratios of four elements.

It is difficult to see how the account might be filled out retaining all of Aristotle's theses about elements and compounds. Moreover, any such elaboration would run counter to the widely accepted view that Aristotle had no notion of a measure of the amount of matter (Jammer 1997, p. 19). But what, then, is to be made of the explicit (if little developed) reference to the "ratio between its constituents" in *On Generation and Corruption* I.10 (and several references in *Meteorology* IV to substances comprising predominantly, or more or less of, one or other of the elements)? Without some such notion, it is difficult to understand how there could be a variety of compounds if all simple substances are to be found in every compound. Note that this otherwise arbitrary restriction might find some kind of rationalisation in terms of the situation portrayed in Fig. 1. At least three elements must be involved if both warmth and humidity are to take on intermediate degrees, and perhaps it is natural to think that a unique resolution of the intermediate degrees characterising a compound into extreme degrees would involve all four elements. But then there must be some additional magnitude contributing to the analysis.

There are pointers in Aristotle's texts to a solution to the problem of elemental proportions which are worth pursuing because of the issues they would resolve, despite the tensions raised for the interpretation of Aristotle. These pointers have, however, been understood differently. Consider a problem raised by Freudenthal (1995) who assumes from the outset that Aristotle has a definite notion of elemental components being *preserved* in a compound. Freudenthal says this immediately poses a problem of stability. Preservation of a compound is threatened, given this assumption, because of the conflict between the contrary defining features of the elements and because of the inherent tendencies of the elements to move off towards different parts of the universe.[10] As a leading exponent of thermodynamics, Duhem was well aware of the

10 Even Gill, who interprets Aristotle to say that the elements are not preserved in a compound (1989, pp. 79, 149, 151, 212), and are merely potentially recoverable

problem of stability, which this science tackles in terms of describing conditions for equilibrium under prevailing constraints. This problem gives some insight into why Duhem may have been attracted by the Aristotelian conception according to which, as he understood it, "elements … cease to exist at the moment when the mixt is created, and the homogeneous mixt whose smallest part contains the elements potentially … can regenerate them by the appropriate corruption" (1902, p. 182). On this understanding, there can be no conflict between contrary defining features of the elements in a compound, as Freudenthal would have it, the extreme contraries having given way to an intermediate degree. The second source of instability in Freudenthal's scenario introduces features which are new to the present discussion, namely the intrinsic heaviness or lightness of the elements. These features are expressed by the tendency, as the Aristotelian view has it, of earth to fall towards the centre of the universe, of fire to rise towards the upper reaches of the region bounded by the sphere defined by the lunar orbit, and of water and air to move to intermediate regions. Earth is said to have an

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rather than mechanically separable like oil floating on water, develops much the same idea. Organisms preserve their identity by means of an active principle which counteracts this inherent instability of the compound substances of which they are made, much as a static force enables a pillar to hold up a bridge, without incurring any change: "if the soul were not present to prevent dispersion, the parts of composite bodies would scatter according the nature of their elements" (1989, p. 212). But the thesis of the inherent instability of compounds is deeply perplexing given the general theory of chemical reaction developed in *On Generation and Corruption*, according to which determinate degrees of the primary qualities lead bodies of the same order of size to attain values intermediate between the original degrees. If this isn't the description of a process driven towards equilibrium, what is it? Why should contrary degrees of warmth and humidity be said to make the original ingredients act and be susceptible to action if it now turns out that they don't lead to a state of equilibrium but ulterior forces are required to constrain the product of such a reaction to remain in the same state? A commentator faced with the problem of interpreting the entire corpus might have to acknowledge that Aristotle says some such thing; but in that case, the question of the coherence of the whole might also be addressed. Coherence is threatened by the *extraneous* cause of instability due to contact (Aristotle doesn't allow a vacuum) with other homogeneous bodies of different kinds, which should eventually lead to the elimination of all differences of substance with the attainment of an intermediate degree of warmth and of humidity throughout the sublunar region—the soggy, tepid death of the universe. Organisms count for only a small part of the material.

absolute heaviness because it falls in every other medium, whereas water has a relative heaviness because it falls through fire and air but not earth, as does air because it falls through fire. Similarly, fire is absolutely light, and air and water relatively light (*Cael* IV.1, $308^{a}29$ff.).[11] The notion of the simplicity of the elements is introduced in *On the Heavens* with reference to these inherent qualities of heaviness and lightness:

> Bodies are either simple or compounded of such; and by simple bodies I mean those which possess a principle of movement in their own nature, such as fire and earth with their kinds, and whatever is akin to them. Necessarily, then, movements also will be either simple or in some sort compound—simple in the case of the simple bodies, compound in that of the composite—and the motion is according to the prevailing element. (*Caelo* I.2, $268^{b}27$-$269^{a}3$)

It therefore seems reasonable to look here for a third independent relation governing the ratio of constituents in a compound. This is at least in agreement with Freudenthal in so far as, in treating lightness and heaviness as a second source of instability, he takes these properties to be irreducible to warmth and humidity. And as already indicated in section 3, whether or not the general strategy of *DG* II.2 is to be understood as encompassing such a reduction, there is not the slightest hint there of how such a reduction might be conceived.

In Needham (1996, p. 267) I made the simple suggestion that the equilibrium position of a quantity of a compound along a radial line terminating at the inner boundary of the superlunary region is the result of the earth content pulling downwards and the fire content pulling upwards. Although this suffices, in conjunction with equations obtained from the relation of the intermediate degrees of warmth and humidity to the ratios of sums of amounts of elements carrying the corresponding extreme degrees, to determine the ratios of the elements, it oversimplifies what Aristotle says. Why shouldn't the relative heaviness and lightness of the other two elements be taken into account? This would involve complications of considering the medium in which the body comes to rest in order to determine whether, for example, air's relative lightness or relative heaviness comes into play. But before getting involved with such details, the entire proposal might be considered off track because Aristotle speaks of motion rather than rest in this last passage, and the relevant observable feature should be speed of descent or ascent rather than position. (There is disagreement, however, on whether this is speed of free fall (O'Brien 1995) or of one arm of a counterweighted balance (Lewis 1995).) Moreover, it seems that Aristotle means that "motion is

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[11] Note that the converse of the heavier than relation, the relation of being less heavy, is not to be identified with being lighter. Similarly for the converse of the lighter than relation.

according to the prevailing element" in the sense of according to its *preponderance*, i.e. the amount by which it exceeds the other, based on differences between, rather than proportions of, the elemental constituents (O'Brien 1995, p. 69; Lewis 1995, p. 94; cf. *Caelo* IV.4, 311ᵃ30-3). This second line of approach involves considerable complications of its own, however. But note that it also implies a certain shift in assumptions about what is at issue. The preponderance idea calls into question Jammer's claim, that "[w]eight, in ancient thought, was … intensive rather than extensive" (1997, p. 18). Aristotle is confusing on this point. Some passages clearly suggest that the relations of heavier and lighter are intensive notions, as when he says "[b]y lighter or relatively light we mean that one, of two bodies endowed with weight and equal in bulk, which is exceeded by the other in the speed of its natural downward movement" (*Caelo* IV.1, 308ᵃ31f.). Again, reference to kinds of matter combined with no reference to bulk, as when he says "[o]f two heavy things, such as wood and bronze, we say that the one is relatively light, the other relatively heavy" (*Caelo* IV.1, 308ᵃ8-9), also suggests intensive notions. But he certainly had extensive conceptions: "[t]he larger the quantity of air the more readily it moves upward" (*Caelo* IV.2, 308ᵇ27).

Not only the proportions of the elements, but also the amount of each in a given quantity of a compound are involved when taking into account the idea that preponderance determines motion. This is more than the three independent ratios required to determine composition, calling for more information than the original problem required. O'Brien and Lewis provide no solution to that problem, but simply take the idea of elemental proportions for granted when explaining how the preponderance of some elements over others might be understood to give rise to different speeds of descent or ascent (O'Brien 1995, p. 69; Lewis 1995, pp. 96-7). To give some idea of the kind of relation envisaged without going into their differences of opinion, suppose we have two quantities, π and ρ, of different kinds of compound (such as bone and flesh). If E_π were the earth content of π, W_ρ the water content of ρ, and so on, then consider how elemental differences might determine which of π and ρ falls faster in a given medium, say air. Let us suppose that air doesn't fall in air, and so the air content makes no contribution. In that case, the speed of fall in air of π is greater than that of ρ if

$$(E_\pi + W_\pi - F_\pi) > (E_\rho + W_\rho - F_\rho),$$

i.e. if the net excess of heavier over light constituents in π is greater than that in ρ. Clearly, the "if" cannot be strengthened to "if and only if" since different combinations of constituent amounts can give rise to the same net excess.

We might speculate that a calibration of speeds of fall is possible on the basis that, for a given volume, pure earth falls fastest (although greater volumes of pure earth fall faster), and a quantity π (of the appropriate volume) for which $(E_\pi + W_\pi) = F_\pi$

remains at rest in air. (If $(E_\pi + W_\pi) < F_\pi$, π would rise in air.) This brings us back to my original suggestion, with the modification that the attainment of an equilibrium position depends both on the medium and the volume of the quantity of the compound substance. For the particular volume of the compound substance which floats unhindered at a certain height in air, we have a third equation, independent of those governing the degrees of warmth and humidity,[12] sufficient for determining the ratios of the constituent elements. Following Lewis's suggestion (1995, p. 90) that the speeds concern differences in amounts of material on two arms of a balance, the calibration of speeds of fall might be considered to provide a measure of the total amount of matter in different volumes of the same substance.

Resolving the problem of composition (ratio of constituents) along these lines involves a good deal of speculation, and consequently may not provide a solution to the problem of interpreting Aristotle's view. There is therefore little point in discussing variations on the theme. But it is important to show that some definite sense can be made of the notion of the elemental proportions in a compound conceived along Aristotelian lines, at least in principle. Armed with such a notion, an issue left open at the end of §3 can now be taken up again.

7 What bears the Aristotelian potentialities?

Aristotle's notion of the potential presence of the elements seems to involve a claim to the effect that a compound is possibly earth, water, air and fire. There is an unclarity here. But to simplify the discussion an unAristotelian example—though appropriate for anyone like Duhem, interested in applying Aristotle's ideas in a more modern context—is chosen in terms of which the essential points will be made. Water will be considered as a compound with hydrogen and oxygen as components. The initial claim is then that

Water is possibly hydrogen and oxygen.

This would seem to mean that of any given quantity of water, say π, a certain modal property is true of it, as expressed by

π is possibly hydrogen and oxygen.

But what, exactly, bears the property of being possibly hydrogen and oxygen, and how should this modal conjunction be understood? It is surely not possible that the whole of π is possibly hydrogen, nor that the whole of π is possibly oxygen. An appropriate insertion of "partly" would seem to be called for. We might try

π is partly possibly hydrogen and π is partly possibly oxygen.

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12 And perhaps a fourth, of the form $E_\rho = (A_\rho + F_\rho)$, for a different volume which comes to rest in water.

I.e., there is a part of π, say ρ, which is possibly hydrogen, and there is a part σ of π which is possibly oxygen, these two parts being mutually exclusive and jointly exhaustive. This could be put by saying that for any given quantity, π, of water

$$(1) \qquad \exists\rho\,(\rho \subset \pi \;\wedge\; \Diamond(Hydrogen(\rho) \;\wedge\; Oxygen(\pi - \rho))),$$

where $\subset$ is the mereological relation of proper part (excluding the possibility of identity) and $\pi - \rho$ is the mereological difference or remainder of π less ρ; i.e., what remains of π when ρ is removed. (Formally, this difference is defined as the sum of all those quantities which are a part of π and separate from (don't overlap) ρ.) $\exists\rho$ is the existential quantifier, read, "there is a ρ such that …," $\Diamond$ is the modal operator, read "it is possible that …," and $\wedge$ means "and."

(1) expresses a sense in which the elements are potentially present in a compound. But, it might be objected, any proper part ρ' of a part ρ said to be possibly hydrogen is in fact water, and so some part, ρ'', of it (ρ') is, by the same count, possibly oxygen. Now if the whole of ρ is possibly hydrogen, by virtue of homogeneity presumably every part of ρ is too, so the part ρ'' of our arbitrary part of ρ is not only possibly oxygen, but possibly hydrogen too. This doesn't threaten contradiction, however, since

$$\Diamond\varphi \;\wedge\; \Diamond\psi \;\;.\!\supset\;\; \Diamond(\varphi \;\wedge\; \psi),$$

where $\supset$ denotes implication, is a notoriously invalid principle for an acceptable modal logic, and so

$$\Diamond Hydrogen(\rho'') \;\wedge\; \Diamond Oxygen(\rho'')$$

doesn't imply

$$\Diamond(Hydrogen(\rho'') \;\wedge\; Oxygen(\rho'')).$$

(Compare an earlier quote from Gill stating that (a quantity of) earth is potentially clay and potentially wood; this doesn't imply that the quantity is potentially both clay and wood.) But as it stands, (1) hardly does justice to the homogeneity of the compound, which requires that there is no definite or unique division of a quantity of water into two parts, one of which is possibly hydrogen while the other is possibly oxygen. As Aristotle put it, the idea that a compound is "composed of the elements, these being preserved in it unaltered but with their small particles juxtaposed each to each," raises the problem that "Fire and Water do not come-to-be out of any and every part of flesh." He was looking for an account which, just as "a sphere might come-to-be out of *this* part of a lump of wax and a pyramid out of *some other* part, it was nevertheless possible for either figure to have come-to-be out of either part indifferently," would describe "the manner of coming-to-be when both come-to-be out of any and every part of flesh" (*DG* II.7, 334^{a}29ff.). Duhem expresses some such idea when, in the passage already quoted at greater length, he speaks of a "homogeneous mixt whose smallest part contains the elements potentially …[and] can regenerate them by the appropriate corruption" (1902, p. 182).

(1) doesn't actually say that there is a unique partition of π into what is possibly hydrogen and what is possibly oxygen; an additional clause would have to be added to the effect that no distinct such partition exists. But (1) is compatible with such a uniqueness claim and should therefore be elaborated with an additional clause inconsistent with the uniqueness claim and more in line with the Aristotelian idea that, in some sense, any part of water might be partly hydrogen. There is a restriction on this idea, however: there is no unique partition, but any particular partition stands in the same proportion as any other. Let "$SameRatio(\pi,\rho,\sigma,\tau)$" abbreviate the relation of the ratio of π to ρ being the same as that of σ to τ. Then, for any given quantity, π, of water, (1) can be elaborated to read:

(2) $\exists\rho \subset \pi\, (\Diamond(Hydrogen(\rho) \wedge Oxygen(\pi - \rho)) \wedge \forall\sigma \subset \pi\, (SameRatio(\rho, \pi - \rho, \sigma, \pi - \sigma) \supset \Diamond(Hydrogen(\sigma) \wedge Oxygen(\pi - \sigma))))$,

where $\forall\sigma$ is the universal quantifier, read "for all σ, …."

If a large and a small lead ball are melted and mixed, and the resulting quantity divided into two balls, a larger and a smaller in the same volume ratio as the originals, there is no saying whether the matter of the resulting larger ball is identical with that of the original or not. Similarly on the Aristotelian conception of a compound, quantities of hydrogen and oxygen may be combined to form water which is subsequently reduced to its elements, but there is no saying whether the matter of the original quantity of hydrogen is identical with (as distinct from being of the same kind as) that of the resulting quantity.

8 Conclusion

Aristotle's theory of substances and their interconversion is certainly not without its problems. It by no means follows that any of the opposing views from antiquity were in any better shape, and it is doubtful whether they should be considered any closer to modern views. I have tried to present Aristotle's contributions to the development of ideas in chemistry in a more positive light than is usually done.[13] Some of his insights can be summarised in this final section.

1. The fundamental issue in chemistry is the generation of new substances from old by chemical reactions. Aristotle recognised that this required an account of how initial ingredients in a mixing process can affect and be affected by one another so as to bring about the formation of new products.

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[13] See, for example, Horne (1966).

2. What is it that distinguishes one substance from another? It is not clear that the atomists had any idea of substance, but merely postulated vast numbers of small particles displaying in principle infinite variations of a more or less radical kind with no general principle of collection under chemical kinds. Aristotle saw an appropriate criterion in the distinction between homogeneous and heterogeneous matter: homogeneous material comprises a single substance—either an element or a compound—whereas heterogeneous matter comprises a mixture of several substances.

This principle was evidently abandoned with Lavoisier's analysis of water, which proceeded by reducing steam, and can't meaningfully be thought of as in any particular phase when ascribed a composition of hydrogen and oxygen. But the alternative view was first systematised with the discovery of the phase rule one century later.[14] Even if Aristotle got some important features wrong, the idea of a fundamental relation between phase and substance is retained and elaborated in modern science rather than being entirely overthrown.

3. What we call a phase change involves a discontinuity. Aristotle recognised a discontinuity in the first of the two kinds of mixing that he distinguished, which are not such that the one goes over into the other continuously. Rather, there is an abrupt change when one body is so much larger than another as to overwhelm it. Although Aristotle's specific theory of phase is rejected, it should be acknowledged that he grappled with a phenomenon that we still recognise as standing in need of an explanation.

4. It may seem that the characteristically Aristotelian idea of potential presence has been abandoned. It was said here that the post-Lavoisian view is usually taken to view elements as preserved in compounds. But the modal element has not been entirely dispensed with. Clearly, the actual presence of elements in compounds cannot be upheld in virtue of the properties exhibited by elements in isolation, so that quantities of matter characterised by certain properties exhibited in isolation must be understood to potentially possess other features exhibited by compounds; and conversely, the matter of compounds must be understood to potentially exhibit certain properties in isolation. Characterisation of the elements by the periodic table complements any lists of properties exhibited in isolation with potential properties which the elements would exhibit were they combined in compounds. Otherwise, definition in terms of actual properties would exclude what is ordinarily counted as matter of the same element kind in a different state of chemical combination.

Fixing on atomic structure does not circumvent this general feature. The electronic structure characteristic of isolated atoms, or of atoms in molecules of the isolated

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[14] Cf. Needham (2000) and (2002b) for discussion.

element, is changed in compounds. Preservation of nuclear structure, even if necessary, is clearly not sufficient to explain the presence of elements whose chemical features are supposed to specifically depend on electronic properties. The fact that considerations of this kind led Paneth (1962) to question whether modern chemistry has dispensed with the Aristotelian conception of an element is a good indication that the conception doesn't stand or fall with the continuous conception of matter.[15]

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