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# ARISTOTLE'S CONCEPT OF MATTER AND ITS RELATION TO MODERN CONCEPTS OF MATTER*

## 1. INTRODUCTION

In this paper I want to analyze in some detail Aristotle's concept of matter. I do so not simply as a matter of historical scholarship, but in the interest of defending the correctness both scientifically and philosophically of what I would call the central doctrine. The elusiveness of Aristotle's detailed remarks on the concept of matter is notorious, and I shall not take it as my task to attempt to square my account with every passage that can be cited in the major works. I shall give references where they are obvious and appropriate. In some cases I shall assert features of his doctrine that are not properly documented in the text, but that I think are features of his concept of matter that are pretty generally accepted.

I also am not concerned to defend the details of all of his explicit beliefs. For example, what he has to say about the sun and the earth and the nature of circular motion is clearly false in detail. I am sure that if he had been presented modern astronomical evidence, especially astrophysical evidence about the swirling chaos of low density matter in outer space, he would have changed his views. Errors in detail of this kind seem to me to be of no importance. The basic doctrine, it seems to me, is correct. Moreover, I want to claim that it is correct in a strong sense: it can be used as a basis for interpreting the results of modern science. Defenders of Aristotle's concept of matter have been too defensive about the place of his concept in modern physics. I shall at the end of the paper attempt to put the case as strongly as I can for the correctness of Aristotle's view in the light of the best current knowledge about the nature of matter, as that term is ordinarily used by physicists. I am of course not suggesting that modern physicists talk about Aristotle or use in any obvious way an Aristotelian concept of matter. I do want to argue that they would often be better off if they did. Certain tendencies of research might indeed be improved if more heed were paid to Aristotle's doctrine than to the atomic theory we all tend so naturally and naively to accept. I think that

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it is very much a part of educated common sense at the present time to accept the building-block theory of matter in terms of atoms and molecules. We think of the spatial array of a molecule in terms of atoms, and we think of atoms as small planetary systems made up of simpler elements, such as electrons and protons. This building-block theory of matter is in detail obviously wrong. More importantly, it is conceptually wrong, and I want to argue that in spite of the importance for the history of science of the development of atomic views of matter in the nineteenth century and in the first part of this century, this aberration, like the aberration of universal determinism derived from classical particle mechanics, is mistaken.

I have organized my analysis in the following way. In the next section I state the central features of Aristotle's doctrine. After that, I compare this doctrine with modern scientific concepts of matter. Next I compare Aristotle's doctrine of matter with that of Descartes, Boscovich and Kant, in order to get a perspective on the philosophical thinking that parallels the development of modern science. In the final section I reexamine how Aristotle's concept of matter can be related to specific scientific theories of matter. I end with the strong claim that Aristotle's basic ideas are appropriate and proper for modern science.

## 2. Central features of Aristotle's doctrine

I have organized the features I want to emphasize under ten headings. I have not given under these headings a thorough account of Aristotle's doctrine of substance or his doctrine of motion, both of which are closely related to his concept of matter. I have tried to concentrate only on those features that are in my judgment most essential to his concept of matter.

(1) *Matter is the substratum of change. "For my definition of matter is just this – the primary substratum of each thing, from which it comes to be without qualification, and which persists in the result" (Physics,* 192a31; see also 190a15, 226a10, *Metaphysics*, 999b5, 104a32).

Matter as the substratum of change is perhaps the most characteristic aspect of Aristotle's doctrine of matter. It is important to keep in mind the relative concept as well as the ultimate one. In one sense the matter of the statue is the bronze from which it is made, yet the bronze itself is not ultimate matter but has itself various qualities such as heaviness and color. The rather delicate problem of how to talk about ultimate matter is discussed below in greater detail.

By putting Principle (1) first I also mean to emphasize the central physical character of Aristotle's concept of matter. Uses of the concept of matter as in talk about the matter of an argument or the matter of a geometrical line are taken to be clearly derivative and are not considered in any detail here.

(2) *A substance has both form and matter. The nature of a substance is complex. It is neither simply the form nor the matter* (*Physics*, 191a10, *Metaphysics*, 1043a15, and many other possible citations).

The distinction between substance and matter is critical for Aristotle. A substance is never pure matter. There are cases apparently in which the principle stated here is contravened in the other direction, however. It is possible to argue that according to his view the stars, for example, are substances that have no matter. I refer to this below, but for sensible substances of the kind that form the subject of the analysis of change, both form and matter are required.

(3) *Matter qua matter is purely potential and without attributes (Metaphysics,* 1029a19*). It is realized or 'actualized' only by some form. Consequently, matter as such cannot be properly defined (Metaphysics,* 1043b30, *Physics,* 194b8*).*

Principle (3) is fundamental for Aristotle's theory of matter. It is wrong-headed from his standpoint to ask of a substance what is its form and what is its ultimate matter and then to ask for properties of the matter. This view of matter seems contrary to that of contemporary physics with its talk about the quantity of matter or mass as an invariant property of matter. It must be realized that in talking about matter in this way physicists are not talking about matter in the way that Aristotle does. In abstract classical dynamics, for example, the only property of matter that is admitted is its mass, but even this admission is not consistent with Aristotle's doctrine of matter as pure potentiality. The evident contradiction between these two ways of talking about matter does not mean that one is wrong and the other is correct – it means that the word *matter*, or its translation in various natural languages, is being used in more than one sense.

More importantly, Aristotle's own views divide naturally into statements about relative matter and statements about ultimate or prime matter. Contrary to Principle (3) it would be appropriate for Aristotle to ask about the properties of the relative matter of a bronze statue, for this is just to ask about the properties of bronze. It must also be conceded that many, if not most, of Aristotle's own remarks about matter are about relative matter not prime matter. The reasons for this should also be obvious. If we simply plunge from questions about the bronze statue to questions about its ultimate or prime matter, there is not much we can say that is appropriate, but this incongruity is no different from plunging into a modern analysis of the molecular structure of bronze.

The next two principles I want to discuss together.

(4) *There is no principle of individuation for matter qua matter.*

(5) *The principle of individuation for substances does not require sameness of matter for sameness of substance.*

Because matter qua matter is pure potentiality there are no attributes that can be used to characterize a principle of individuation for matter. (Note that in referring to matter qua matter here and earlier, I have in mind ultimate or prime matter, and thus an essentially equivalent formulation of Principle (4) is that there is no principle of individuation for prime matter.) On the other hand, we can use matter in differentiating some substances; for example, I can be holding two rocks and differentiate them by the fact that though their attributes seem to be the same they are composed of different matter. On the other hand, sameness of substance does not require sameness of matter. We talk about a physical body's being the same even though its matter may have changed; for example, a human body is both intaking and excreting substance, but we still speak of the identity of that human body through time.

There is a close parallel between the absence of a principle of individuation for matter and the problems of individuating points in space. One schematic way of describing the situation is in terms of observing in space the occurrence of some physical process or act. An example will suffice. Suppose we want to predict the height of the tide on the Pacific side of the Panama Canal two weeks from now at 0400 hr. Following a standard methodology we can represent the heighth of the tide measured by a vertical rod as a random variable with a given continuous probability distribution. For present purposes, it is useful to think of a 'question' with a yes-no answer as any interval on the measuring rod (technically we want not just intervals but any Borel set generated from intervals). If the tide follows within a given interval, the answer to the question posed by choosing that interval is yes, otherwise, no. Now suppose we consider two intervals, one being the closed interval [2 m, 3 m], and the other being the open interval (2 m, 3 m), the difference being that the first includes the two end points, 2 meters and 3 meters, and the other does not. Then our probability prediction will be the same for both intervals, and so will our claim that the observed tide falls within each interval. Our methodology of observation is not even in principle refined enough to discriminate between these two intervals, and this means our methodology does not permit us to individuate individual points, but only intervals of points. In this case points thus play a role analogous to that of prime matter.

Still another example of such a lack of a principle of individuation can be found in classical Zermelo-Fraenkel set theory with individuals. In a set theory of this sort, there is no satisfactory principle of individuation for individuals. It might seem appropriate to say that two individuals are identical if and only if they belong to exactly the same sets, but the identity of sets as formulated in the axiom of extensionality just depends upon two sets being identical if and only if they have the same members. So in such a set theory, as might be expected, we have no principles for asserting a principle of individuation for individuals. This of course is not surprising, because we have not built any structure that deals directly with individuals into the fundamental axioms. Indeed, with certain reservations, such a set theory with individuals constitutes a model for a fair number of the principles being stated in this section.

(6) *Substance has no contrary, but rather contraries like hot and cold are attributes of substance, and contraries can be attributes of the same substance at different times.*

For example, I may say that this pot is now hot, but it was cold when I started the fire a few moments ago. The pot itself does not have a contrary but its attributes go from the attribute it now has to the contrary of this attribute, for example, from cold to hot. I shall have more to say about contraries after the statement of the next principle.

(7) *Only things or substances that change have matter (Metaphysics,* 1044b27). *Change is connected with the potentiality of opposites (Metaphysics,* 1050b26*).*

The contraries occupy a central role in Aristotle's theory of matter and of substance. What he has to say about these matters seems to me quite sensible, even though much of the talk on the surface seems very old-fashioned and far from talk of modern physics. The reason for this is not so much that the idea of contraries is now of no use but rather the kinds of examples he uses are not of great importance in physics itself; i.e., the concepts of hot and cold, for example, are replaced by the quantified concepts of heat and temperature, and more generally, the contraries represent a kind of qualitative theory of measurement that in most instances is replaced by a quantitative theory. In the subsequent analysis I shall not have much to say about the contraries, but it should be recognized that the doctrine of contraries is intimately related with the doctrine of matter as substratum, and it is not coherent to have a doctrine of matter as a substratum without something like a doctrine of contraries. The essential correctness of Aristotle's theory of contraries is represented by their continual use in ordinary talk. The scientific task has been not to establish the incorrectness of the contraries, but rather to provide a deeper-running quantified theory of the phenomena they describe.

I have avoided here the difficult problem of the generation and destruction of substances, and the analysis of contraries that is attached to the four elementary substances (e.g., *Physics*, 189b). The last chapter of Book I of the *Physics* does seem to yield a relatively straightforward argument for the conservation of prime matter, but since an explicit conservation law seems contrary to the spirit of Aristotle's view, I have omitted a separate statement of such a principle. It does seem needed in any attempt to make explicit the theory of generation and destruction of primary substances.

(8) *The matter of a body or substance is not the place of the body or substance, and is not therefore that which contains the body or substance. Put another way, the matter of a body or sub-*

*stance cannot be identified as the container of that body or substance (Physics,* 209b22 and 211b30*).*

This principle is a clear enunciation that matter is not space and a container theory of matter is not part of Aristotle's doctrine. I highlight it here because it is, under one interpretation, in direct contradiction with Descartes's theory of matter as extension, which I discuss in Section 4.

(9) *The void does not exist as a separate thing or substance. The most that can be said is that "the matter of the heavy and the light, qua matter of them, would be the void" (Physics,* 217b22*).*

This principle I include to separate Aristotle from the classical atomistic tradition and, for example, from the theory of matter advocated by Boscovich. More importantly, the idea of empty space has been central to atomic doctrines, both ancient and modern, but it is also true that since the discovery that light and other electromagnetic phenomena are propagated with finite velocity there has been little tendency to accept the void as a serious physical concept. It is also part of this principle that Aristotle does not accept that matter is made up of indivisible homogeneous simple elements that exist in a void. In other words, the atomic theory of matter is inconsistent with Aristotle's.

(10) *The sun and stars have no matter; their motion does not involve the potentiality of opposites; circular motion has no contrary (On the Heavens,* 270a12; *Metaphysics,* 1050b22*).*

As indicated earlier, this principle of Aristotle seems mistaken, but I do not take the mistake to be a serious one.[1] On the basis of modern evidence I am sure it is the one principle of the ten that he would have changed. It seems to me that the remaining ten can stand essentially unaltered. I do not mean that there are no other statements of Aristotle about matter that need correction, but of the features that I consider characteristic of his doctrine, it is only this last that seems to me to be clearly and unequivocally in error. The error is in a major application of the general theory, not in the general theory itself.

## 3. Modern scientific concepts of matter

Before examining in more detail Aristotle's concept of matter it may be of some value to relate it in a general way to modern concepts of matter. There are two great traditions to be examined. One is the philosophical tradition and the other is the scientific. In the earlier period, of course, these traditions were not sharply separated. I take as prime examples of the philosophical tradition Descartes, Boscovich and Kant. Descartes and Boscovich both thought of their contributions as being part of science as well, insofar as there was any clear separation between philosophy and science in the seventeenth century and in the framework of the eighteenth century within which Boscovich operated. Kant clearly separated his own contribution, especially the metaphysical foundations of natural science as set forth in the work of that title. The scientific tradition, on the other hand, is associated with the development of atomic theories of matter in the nineteenth century and the deep development of particle physics and quantum mechanics in the twentieth century. It is characteristic of the scientific tradition that it is difficult to find explicit and categorical answers to the question, What is matter? The view of matter that may be inferred from the scientific tradition is, however, often fairly obvious. It would take us too far afield to try to examine the history of that development in detail. It may be useful to say something about it before turning back to the philosophical tradition.

Certainly one conclusion that can be drawn is that even implicitly there seems to be nothing close to Aristotle's concept of prime matter in the scientific developments since the end of the eighteenth century. Much of the initial thrust was to revive and actually develop a very viable theory of atoms, a theory that certainly is closer to the ideas of Democritus than of Aristotle. In the latter part of the nineteenth century electromagnetic theory and the experiments connected with the development of special relativity create an atmosphere that is more congenial to Aristotle's ideas, but the remoteness of these developments from Aristotle is exemplified by the fact that in E. T. Whittaker's exhaustive *History of the Theories of Aether and Electricity* (1910) there is no mention of Aristotle whatsoever. Of course, it is possible to attribute this to ignorance on the part of the scientists responsible for the theories of the ether and electricity, and it is even possible to attempt to claim that the concept of the ether is itself closely related to Aristotle's concept of prime matter. However, a little reflection indicates that this is a futile hope. Certainly it is completely inconsistent with Aristotle's characterization of matter to attempt to build the kind of mechanical model of the ether for which Lord Kelvin and Maxwell are famous. The definite attribution of mechanical and electrical properties to the ether is inconsistent with Aristotle's conception of prime matter as pure potentiality. In fact, the main thrust of the nineteenth-century models of the ether was to apply the relatively deep mathematical and conceptual developments of the mechanics of fluids to the construction of mechanical models of the ether, with the addition possibly of separate and independent electromagnetic properties.

It must also be recognized that from the end of the nineteenth century and through the development of quantum mechanics, the acceptance of the electron as a fundamental particle of an indivisible and fixed character with definite mass and charge is very much in the spirit of Democritus and atomism, rather than in the spirit of Aristotle's physics, just as was the case a hundred years earlier in the development of the atomic theory of matter. I know of no serious discussion that relates Aristotle's concept of matter to the theory of fundamental particles running from, say, 1890 to 1930.

There are two further remarks I want to make about Aristotle's concept of matter in connection with modern scientific theories of matter. The first concerns axiomatic foundations of modern theories. It might be thought that even though the formulations of theories of matter by physicists do not invoke a concept at all close to Aristotle's this is simply due to their leaving implicit major assumptions. It is well known, for example, that foundational discussions of physics do not in general satisfy the most rudimentary mathematical standards of explicitness from an axiomatic standpoint. It might be felt that an explicit axiomatic theory of mechanics or electromagnetic theory would bring out closer connections between Aristotle's theory of matter and contemporary scientific theories. The contrary seems to be the case.

If we consider, for example, axiomatizations of particle mechanics, we take as undefined or primitive the set of particles but immediately attribute properties to these particles, especially mass. As we move on to more complicated objects like rigid bodies we attribute additional fixed properties like those of moment of inertia. When we turn to electromagnetic theory we encounter attribution of charge or, in the case of electromagnetic fields, measures of intensity of the field that are meant to be in principle observable. Nowhere in such discussions is there a hint of something corresponding to Aristotle's distinction between form and matter.

There is one possible exception to these remarks; it is the case of classical continuum mechanics, to which I return in Section 5.

The second remark concerns the apparent instability of current concepts about elementary particles and the general chaos of theory in high energy physics. When it was thought that there were a few fundamental particles out of which everything else in the universe was composed and that these particles were themselves indestructible and in some clear sense elementary simples, then the atomic theory of matter seemed to have won the battle, even if the elementary particles did not possess all the properties we expect of macroscopic bodies. Research in physics of the last couple of decades has shown that this picture is not at all the correct one. The number of particles has been shown to be very large, and there is now some skepticism that any simple account in terms of a few fundamental particles will ever be made to work. Certainly it would seem that the present situation in high energy physics is much more congenial to an Aristotelian theory of matter than the situation that obtained even 30 years ago. I shall have something more to say about these matters in Section 5.

## 4. Some comparative philosophical concepts of matter: Descartes, Boscovich and Kant

If philosophical developments closely followed the scientific developments just sketched, then little sign of Aristotle's influence on modern philosophical concepts of matter would be expected to be found. If we look at the most influential concept of matter in the seventeenth century, the century that ushers in modern science, then all traces of Aristotle seem to have disappeared. I refer of course to Descartes's concept of matter. This also seems to be true when we look at Boscovich's influential views in the eighteenth century, but the situation is quite different when we come to Kant.

To provide a broader framework for analyzing Aristotle's concept of matter, I shall briefly examine the concept of matter advanced by each of these three philosophers.

The most systematic exposition of Descartes's physical theory is to be found in his *Principia Philosophiae* (1644). Part II of this treatise is concerned with the general principles of material things that can be known clearly and distinctly. In this part are established a large number of general propositions concerning the nature of matter, the existence of atoms, the laws of motion, etc. As is well known, Descartes attempts to describe and explain the physical world in terms of nothing but extension and motion. The fundamental characteristic of matter or body is extension (I, Art. 53, II, Art. 4).[2] This property of extension is the only clear and distinct idea of body that we can have (I, Art. 54, Art. 63, II, Art. 1). On the other hand, matter qua extension is obviously undifferentiated, so there is a difficulty to explain the variety and diversity of bodies. Descartes's answer is given in terms of motion, "All the variation in matter, or diversity in its forms, depends on motion" (II, Art. 23). The only kind of motion admitted is of course local motion, and the proper definition of motion is "the transference of one part of matter or one body from the vicinity of those bodies that are in immediate contact with it, and which we regard in repose, into the vicinity of others" (II, Art. 25).

Descartes gives a succinct summary of his theory in the following passage (IV, Art. 203).

> Having considered in general all the clear and distinct notions that can be in our understanding concerning material things, and not having found any of these other than those of figure, size, and motion, and the rules according to which these things can be diversified by one another, which rules are the principles of geometry and mechanics, I judged that all the knowledge that men could have of nature had necessarily to be derived from this only; because all the other notions that we have of sensible things, being confused and obscure, cannot serve to give us knowledge of anything outside us.

There is a great deal of additional detail in the *Principia*, but it is inordinately tedious to read, and we can well believe Gassendi's remark that he knew no one who had read the work in its entirety. The features of Descartes's theory that I have presented here are sufficient to recognize its conceptual inadequacy. Descartes's reduction of the concept of body to that of geometrical solid and his use of a purely relational definition of motion made it impossible for him to give a consistent extension of these ideas from kinematics to dynamics. His own account of forces is a shambles and is simply a reflection of the inadequacy of Descartes's ideas for the development of any serious conceptual framework for physics.

The greater subtlety and empirical adequacy of Aristotle's ideas are evident, and it may seem something of a puzzle to understand why

Descartes's ideas had the enormous influence they did in the seventeenth century. (This influence has been well documented in the classic work of Mouy, 1934.)

Of course, the simplicity and surface clarity of Descartes's prose is enormously appealing in contrast to the Proustian quality of the commentators on Aristotle. In any case, the change from one set of philosophical ideas to another is not a process that we understand very well or have as yet studied with any thoroughness. It is still astounding to find Descartes taken so seriously, but not nearly as astounding as other philosophical examples that could easily be cited.

Boscovich, operating almost a hundred years later, adopted a methodology very similar to Descartes's but in many respects stood Descartes's theory on its head, though he remained as far from Aristotle as did Descartes. The analysis of his concept of matter I give here is restricted to his major work, the *Theoria Philosophiae Naturalis*, which was first published in Vienna in 1758 and then in a revised form in Venice in 1763. (References are to articles of this work.)

In the first six articles, Boscovich states what he has in common with Newton and Leibniz, and how his own theory differs from theirs. His nonextended points are similar to Leibniz's monads, and the mutual forces acting between them are extensions of Newton's ideas about forces. He differs from Leibniz in making his points homogeneous and denying the principle of indiscernibles and the doctrine of sufficient reason. He differs from Newton, he says, by using repulsive forces as well as attractive ones. Boscovich thinks that his greatest achievement was to improve on Newton and reduce phenomena to one principle, his single law of forces. He felt that his chief intellectual debts were to Leibniz and Newton, and in his own mind his relation to the Cartesians is primarily negative. Aristotle plays little part in the explicit discussion of his theory.

The kernel of Boscovich's theory of matter is easily summarized. The matter of the universe is composed of a finite number of nonextended points; attractive and repulsive forces, which are a function of distance only, act between these points according to a single law of forces. All the observed phenomena of nature are to be explained solely in terms of the distribution and motion of these points and the forces acting between them. In his own picturesque phrase, "matter is interspersed in a vacuum and floats in it." (Art. 7)

The principle of the nonextension of matter and the law of forces are the two fundamental hypotheses of Boscovich's theory, but they are not presented as axioms from which verifiable consequences are deduced. Instead, a plausible derivation of them from the more familiar and generally accepted laws of impenetrability and continuity is given. I shall not enter into these details here, but Boscovich's arguments provide indirectly an excellent critique of the Cartesian ideas and bring out inconsistencies in the Cartesian notions.

Boscovich reaches four main conclusions about the primary elements of matter. The first one is that the parts of matter are not contiguous, and the second is that the primary elements are simple, for if they were composite, the indefinitely large repulsive forces would drive the pieces asunder. Boscovich states his view very clearly:

> Now, because the repulsive force is indefinitely increased when the distances are indefinitely diminished, it is quite easy to see clearly that no part of matter can be contiguous to any other part; for the repulsive force would at once separate one from the other. Therefore it necessarily follows that the primary elements of matter are perfectly simple, & that they are not composed of any parts contiguous to one another. This is an immediate and necessary deduction from the constitution of the forces, which are repulsive at very small distances & increase indefinitely. (Art. 81)

The third conclusion about the primary elements of matter is more uniquely Boscovich's own than the first two. It is that the elements are nonextended. The direct argument runs as follows. Since the elements are simple, they cannot have extension of the ordinary sort, but the question arises: can they have what the Scholastics called "virtual extension"? Virtual extension compared with actual extension can for our purposes probably best be understood by giving an example or two. God, who is perfectly simple, is yet everywhere. In the same way, some have argued that the soul is simple and yet (virtually) extended throughout the whole body.[3] Boscovich is willing to admit that it is metaphysically possible that the primary elements of matter possess such virtual extension, that is, that it cannot be proved on metaphysical grounds that they do not (Art. 83). However, on empirical grounds he argues it can be shown that they do not possess virtual extension. If virtual extension were a property of bodies of sensible size, we would be able to observe it. No such observations have ever been made. "Further, this property by its very nature is of the sort for which it is equally probable that it happens in magnitudes that we can detect by the senses and in magnitudes which are below the limits of our senses." Thus, since it is not observed in the one case, we may infer by induction that it does not occur for the primary elements of matter that cannot be directly observed (Art. 84). This discussion of virtual extension is one of the less satisfactory aspects of Boscovich's analysis. It is simply part of his argument to stand fast on the view that the primary elements of matter are nonextended. A good many additional arguments about nonextension are given, especially in Articles 88–90.

The fourth conclusion about the primary elements of matter is that they are homogeneous. Boscovich offers several arguments in support of this conclusion. One argument depends on the law of forces. The curve of forces is the same in its two asymptotic branches for all elements, since all are equally impenetrable and subject to gravitational action. Now there are infinitely many more curves "which, when they differ in the remaining parts, also differ to the greatest extent in the extremes, than there are curves, which agree so closely only in these extremes" (Art. 92). Hence, Boscovich asserts, it is infinitely more probable that the curves agree in all their parts than that they differ between their identical extremes. (Another and rather similar argument is adduced from the similarity of bodies (Art. 96, Art. 97).) The Leibnizian objections to homogeneity on the grounds of the principles of sufficient reason and indiscernibles are rejected with supporting arguments. A vivid analogy using books, letters and dots is used to complete the arguments for this fourth conclusion. Assume a method of printing that prints each letter as a dense series of small, similar black dots (rather like many modern computer printers). From the letters of the alphabet all words used in books are formed. Thus the enormous diversity actually to be found in books can be accounted for by the distribution of many similar black dots. The analogy runs this way. Books correspond to gross bodies. The different substances found by chemical analysis correspond to words. Further chemical analysis discloses a few fundamental particles that correspond to the letters. And finally the dots composing the letters correspond to the simple, homogeneous primary elements of matter (Art. 98, Art. 99).

It seems fair to say that Boscovich's theory represents the thorough working out of the ancient atomistic tradition, and he represents the carrying of this tradition to its finest point. He has, like Descartes, the virtue of offering an extraordinarily simple and clear theory. It is unfortunate that it just turns out to be so thoroughly unworkable and inadequate. It seems to me that in many ways Boscovich's theory represents the fantasies of many physicists, who would like to find that matter is made up of ultimate simples that have exactly the properties predicated of them by Boscovich.

We can see that Boscovich is the opposite of Descartes in affirming that matter is nonextended and that empty space is everywhere, but in the simplicity of his basic conceptions there lies strong affinity to Descartes. Given the great simplicity of Descartes's or Boscovich's ideas, it might seem that there would be little hope of reviving the subtler and more difficult Aristotelian ideas, even if the ideas of Descartes and Boscovich turned out to be wholly inadequate in providing a framework for actual physics.

Kant provides a counterexample. His ideas about substance are much closer to Aristotle's than to Descartes's or Boscovich's. Aristotle's basic argument about substratum, i.e., there must always be something underlying that which is in the process of becoming, is essentially Kant's argument for the existence of substance. It will be worthwhile to look at some of the details.

I shall mainly deal with Kant's views on the nature of matter as set forth in the *Metaphysical Foundations of Natural Science*, but I shall also make reference to significant passages about substance in *The Critique of Pure Reason*. Kant's use of the categories to find the specific determinations of matter is another Aristotelian aspect of his theory of matter. There are some difficult problems about the relationship between the concepts of matter and motion for Kant, and I do not want to enter into these problems in detail here. I have discussed them elsewhere (Suppes, 1967). For the purposes of our discussion here I think we may claim that Kant held that the concept of matter includes the concept of an object of the external sense and that this latter concept includes the concept of motion. Whether this is exactly the correct story, Kant does assert unequivocally that we may reduce all proper natural science to a pure or applied theory of motion. It is then as the doctrine or theory of motion (Bewegungslehre) that the metaphysical foundations of natural science are brought under the four divisions of the table of the categories. In the first division, matter is considered purely according to its *quantity* of motion, abstracted from all its qualities. This gives us the theory of phoronomy or kinematics. In the second division, motion is considered as belonging to the *quality* of matter, "unter dem Namen einer urspruenglich bewegenden Kraft". This yields dynamics. The third division is mechanics; here, motion as quality is considered in *relation* to other reciprocal motions, or, more exactly, matter with this dynamical quality of possessing an original moving force is considered in reciprocal motion. In the fourth division, entitled phenomenology, matter in motion or at rest is considered according to its *modality*; that is, whether in its determination as a phenomenon of the external sense it is determined as possible, real or necessary.

If we left matters at this level of generality, it might seem that there was an enormous similarity between Kant's and Aristotle's theory of matter. However, the special role that Kant assigned to fundamental forces of repulsion and attraction moved the development of his ideas away from a purely Aristotelian framework. Kant emphasizes that the fundamental forces of repulsion and attraction cannot themselves be constructed; their possibility cannot be demonstrated. These fundamental forces are not derived from experience, nor can they be mathematically constructed from other concepts, which would be necessary to demonstrate their possibility. They are jointly the ultimate ground for the possibility of matter. If one asks why matter fills its space by these original forces, the only answer is that they are necessary conditions for the construction of the concept of matter. Reason can do no more than reduce the diverse forces appearing in nature to these two fundamental ones, "beyond which our reason cannot go".

If the fundamental forces cannot themselves be comprehended or explained, if they are each the source of an ultimate explanatory principle, and if the concept of them is used to construct the concept of matter, then the delicate problem arises: of what are these forces predicated? Is it a vicious circle to say they are forces *of* matter? Would it be more nearly correct to say that these forces *are* matter? This is not the same as asking for an explanation of the forces. Rather, accepting them as ultimate, we are asking the different question: to what do they belong, if anything? Boscovich answered this question by making forces ultimate in nature, but retaining as carriers of the forces a finite set of points of singularity. For Boscovich, forces are predicated of these points, which for him solves the question that we are now asking Kant. Kant eliminates all points of singularity in space that might serve as ultimate subjects of the forces. Empty space cannot be an object of experience, and every part, i.e., every point, of filled space possesses forces of attraction and repulsion. Now it is tempting to say that in abolishing all points of singularity and predicating forces of every point of space that can be experienced, Kant has unequivocally adopted a complete dynamical theory of matter and has asserted that forces are matter. There are passages in the Dynamics that lend definite support to this view. For instance, the General Remark on the Dynamics begins: "The universal principle of the dynamics of material nature is: that all reality of the objects of the external sense, which is not mere determination of space (place, extension and figure), must be regarded as moving force...." However, there does not seem to be a fully adequate case for this view. The discussion of substance in the *Critique* forms one of the chief difficulties for such an interpretation. The first analogy of experience states the principle of the permanence of substance. This analogy is the rule corresponding to the category of inherence and subsistence. The principle states that in all changes of phenomena, substance is permanent and is neither decreased nor increased (*Critique*, B224). Substance is simply the substratum of all determinations in time, i.e., of all changing phenomena. Kant's argument is that the bare succession of phenomena must have a permanent substratum as a necessary condition, for this substratum is "the condition of the possibility of all synthetical unity of perceptions, that is, of experience" (*Critique*, A183, B226-27). Without this substratum, the manifold of phenomena given in time could not be determined according to any rules, and could not be connected as objects enduring in time.

The second analogy of experience, which corresponds to the category of causality, is that all changes take place according to the law of causality. For the moment, the important point of this is that changes must be changes in the determinations or states of the permanent substance, one state following another according to a given rule. The permanent substance provides the ground for the connection of successive states; in fact, if substance were created or destroyed, the universality of the law of causality would be violated (*Critique*, B232-33).

But what is the empirical criterion of substance? "Action... is a sufficient empirical criterion to prove substantiality, nor is it necessary that I should first establish its permanency by means of compared perceptions, which indeed would hardly be possible in this way, at least with that completeness which is required by the magnitude and strict universality of the concept" (*Critique*, A205, B250-51). Action directly implies the relation of the subject of causality (substance) to the effect. But for action there is needed the permanent substratum, for "actions are always the first ground of all change of phenomena, and cannot exist therefore in a subject that itself changes, because in that case other actions and another subject would be required to determine that change" (*Critique*, A205, B250). Actions, forces, cannot subsist by themselves but must be determinations of a permanent substratum. On the other hand, Kant says, substance "appearing in space", that is, matter, can only be known to us through the two fundamental forces of attraction and repulsion. Other properties of matter are unknown to us (*Critique*, A265, B321).

Without going further into the systematic discussion of substance in the *Critique*, I believe we may now answer the question we asked about the fundamental forces. Matter, as spatial substance, as the ultimate subject of the science of physics, is not simply the two fundamental forces. It is true that the concepts of these two forces are precisely those that permit us to construct the concept of matter, i.e., represent it in intuition; and simply as an object of intuition, matter is equivalent with them. However, matter as substance is also the permanent substratum of all spatial phenomena. The fundamental forces are not this permanent substratum, but rather it is "the amount of the fundamental forces" possessed by a given part of this substratum that determines its particular state. The mathematician or physicist, dealing as he does only with pure or empirical intuitions, might successfully equate the fundamental forces and matter; but the philosopher, probing at the foundations of the data of intuition, knows that the fundamental forces are not the ultimate subject in space, but are the specific determinations of that subject (the permanent substratum). And this conclusion is supported in the third division of the *Metaphysical Foundations*, where Kant specifically states that the quantity of substance in a matter, that is, the quantity of the permanent substratum, is not a function of the amount of the fundamental forces in that matter, but must be estimated mechanically, that is, by the amount of its motion.

It seems to me that this discussion of force and matter in Kant – the delicate effort he makes to assign a fundamental place to force, and yet not eliminate an independent concept of matter – is still pertinent today. It is particularly relevant to the tangled problems of thinking about force, matter and energy, in any conceptually clear way, in the context of contemporary nuclear physics. I do not mean to suggest that detailed answers for today's puzzles are to be found in reading Kant. I do think that some of the too-simple models we associate with the Cartesian and Newtonian tradition would be more easily rejected as inadequate on general philosophical grounds if we took seriously Kant's careful and discriminating analysis.

Kant's dynamical forces are certainly not a part of Aristotle's theory of matter, but the discussion of substance as substratum is very much in the Aristotelian spirit, and shows clearly enough that Aristotle's fundamental ideas were restored to the mainstream of philosophical discussions of matter by Kant.

## 5. Scientific reconstruction of Aristotle's concept of matter

As I promised earlier, I want to end by making a case for the scientific relevance of Aristotle's concept of matter to contemporary physics. There are three directions of attack I think can be successfully taken. One is in terms of the modern evidence on elementary particles, the second concerns modern work on the foundations of classical mechanics and the theory of bodies in classical mechanics, and the third is the attitude toward the use of random variables in probability theory. I shall only discuss the first two lines of attack in this paper, and reserve the random-variable analysis for another occasion.

As the atomic theory of matter became a workable empirical theory at the beginning of the nineteenth century, it looked certain at that time that the ancient atomic theories of matter were the conceptually correct ones, and all that was left was to work out the details of the interactions of the fundamental atomic parts of matter.

By the end of the nineteenth century it was recognized that atoms have structure, and aspects of this structure were clearly identified. The concept of a nucleus with electrons "in orbit" around the nucleus was developed, and everything seemed once again quite satisfactory. The atom was thought of on the lines of a small-scale solar system, and the fundamental particles were now not atoms, as atoms had been identified earlier in the century, but electrons and protons. It also seemed clear that these elementary particles had fundamental constant properties, for example, a fixed mass (rest mass as the theory of relativity developed), a fixed charge and a negligible but definite size.

As quantum mechanics developed and the many experimental anomalies in the classical picture of the structure of the atom were identified, it became apparent that the particles that make up an atom were not simply little balls bounding around in a small-scale world very much like the one we observe. The properties were peculiar and the theory was tantalizingly elusive. It was also recognized that matter was not indestructible, contrary to ancient ideas of an atomic sort, but that it could be converted into energy. Still, the case for the atomic theory in some form seemed strong, and most physicists probably felt that some version of the atomic theory was basically the correct theory of how the universe was put together. Even if electromagnetic and possibly gravitational fields were admitted, the atomic theory together with some kind of theory of the ether seemed to create a plausible picture.

The pursuit of particles continued and as the energy levels became higher it became apparent that the world is full of particles that are continually undergoing processes of generation and corruption, as Aristotle would put it. Methods for observing this generation and corruption were brought to a fine point by bubble-chamber apparatus and other related methods.

It does not seem to me necessary to fill in the details of this picture in order to describe in qualitative terms how Aristotle's theory of matter fits in. From Aristotle's standpoint, the search on the basis of the evidence available for fundamental building blocks is a clear mistake. The empirical evidence from macroscopic bodies and also from high energy particles is that the forms of matter continually change. There is no reason to think that there is a spatial buildup of electrons, for example, from some more elementary objects. The collisions of electrons and other particles to produce new particles as observed, for example, in cloud-chamber and other experiments is simply good Aristotelian evidence of the change of form of matter. The cloud-chamber data especially support Aristotle's definition of matter. As we observe change there must be a substratum underlying that which is changing. What is the substratum underlying the conversion of particles into other particles, or the conversion of particles into energy? The answer seems to me clear. We can adopt an Aristotelian theory of matter as pure potentiality. The search for elementary particles that are simple and homogeneous and that are the building blocks in some spatial sense of the remaining elements of the universe is a mistake. There is a continual conversion of the forms of matter into each other; there is no reason to think that one form is more fundamental than another. The proper search at a theoretical level is for the laws that describe these changes of form, and not for the identification of elementary particles that are in some fundamental and ultimate sense simple and homogeneous.

In summary, the case seems good for Aristotle's theory of matter providing an excellent way of looking at the phenomena of high energy physics as well as at the macroscopic kind of phenomena Aristotle himself had available. I do not mean to suggest that we can pull any detailed wide scientific laws from Aristotle. What is valuable in his concept is its wide applicability as a way of thinking about physical phenomena.

Kant was right in his criticism of the Cartesian mechanical method, but he was wrong in a way that Aristotle was not in attempting too simple an account of the fundamental forces of nature.

This sketch I have given of the way in which Aristotle's theory of matter can be used to provide a sound interpretation of the proliferation of particles and processes in high energy physics needs of course to be spelled out in greater detail, but it seems to me that its essential soundness is easy to recognize in spite of the broadness of the strokes I have used.

*Classical mechanics of bodies.* It will be useful to end with a more detailed and technical treatment. The reader who is unfamiliar with the manifold problems encountered in the exact statement of the foundations of classical mechanics may think that there is little new to be said about this subject, and that there is scarcely a proper place for the Aristotelian concept of matter. The point I wish to emphasize is that the mathematical and conceptual difficulties of classical mechanics are severe. We are still far from a completely satisfactory general theory. There is, on the other hand, a very substantial gain in clarity and understanding that has taken place in the last decade or two, especially due to the work of Walter Noll, Clifford Truesdell and others. It is fair to say that there has been a renaissance of classical mechanics.

I shall end with a sketch of Noll's (1959) axioms for bodies and their kinematic motion. I shall omit some of the technical mathematical details required for formulating smoothness conditions.

DEFINITION. *A body is a set B endowed with a structure defined by a set $\Phi$ of mappings of B into a three-dimensional Euclidean space E, and a real-valued set function M defined for all Borel subsets of B, subject to the following axioms:*

(1) *Every mapping $\phi$ in $\Phi$ is one to one.*

(2) *For each $\phi$ in $\Phi$ the image of B under $\phi$ is a region in the space E, a region being defined as a compact set with smooth boundaries.*

(3) *The mass function m is a nonnegative measure.*

(4) *For each $\phi$ in $\Phi$ the measure induced by m on the region that is the image of B under $\phi$ is a mass-density function that is positive and bounded.*

Following Noll, we may refer to the elements of $B$ as the *particles* of the body, the mappings $\phi$ in $\Phi$ are the *configurations* of the body. If $a$ is in $B$, and $\phi$ is a configuration, then $\phi(a)$ is the *position* of the particle $a$ in the configuration $\phi$. The set function $m$ is the mass distribution of the body and the density under the mapping $\rho_\phi$ is the mass density of $B$ in the configuration $\phi$.

A motion of a body $B$ is a one-parameter family $\{\theta_t\}$ of configurations $\theta_t$ in $\Phi$ of $B$ such that the derivative $(d/dt)\ \theta_t(a)$ exists for all $a$ in $B$ and all times $t$. The derivative is a continuous function of $a$ and $t$ jointly, and is a smooth function of $a$. Moreover, the second derivative also exists and is piecewise continuous in $a$ and $t$ jointly. (The first derivative is the velocity of the particle $a$ at time $t$, and the second derivative is the acceleration of $a$ at time $t$.)

From these definitions, we can go on to develop a comprehensive though not completely adequate theory of bodies in classical mechanics, where bodies are not just rigid bodies but the sorts of configurations to be encountered in continuum mechanics. They would be covered grammatically, for example, by mass nouns. To complete the development of the present theory we need to add appropriate definitions of body forces and contact forces, and to define the general concept of a dynamical process, but these matters will be omitted here.

Instead, I want to turn to some closing remarks about how Aristotle's ideas of matter may be fitted into this framework, and also to indicate what some of the difficulties are. At one level, the situation seems clear. We simply identify the prime matter of the body as the set $B$ without structure. The introduction of structure corresponds to Aristotle's introduction of forms. The configurations provide the geometrical shapes of the body through time, and the mass function the distribution of density through time. It should also be evident that the particles talked about here are of course not atomic particles or elementary particles in the sense of physics. These are idealized particles that make up a continuum and for this reason they come reasonably close to Aristotle's idea of matter, even though we do use the particles themselves as arguments of functions and thereby in one sense endow them with attributes in a way that he would consider incorrect. I think however that we can take the attitude that the configurations change and therefore we are not endowing a particle, as such, with an attribute, but this is the way of introducing forms.

The important point is that the set $B$ is not like a set of persons or a set of individuals with structure, as for example a set of bronze statues, but is indeed a set that, taken without structure, seems very close to what Aristotle had in mind. I shall close by modifying the first part of the definition of bodies.

> *A body is matter endowed with a structure. We represent the matter by an abstract set $B$ and the structure by a set $\phi$ of mappings of $B$ into a three-dimensional Euclidean point space $E$ and a real-valued set function $m$ defined on the Borel subsets of $B$, subject to the axioms stated above.*

This definition satisfies fairly well the ten Aristotelian 'principles' of matter stated in Section 2, but, of course, Principle (10) concerning the heavenly bodies does not really apply. I say "satisfies fairly well", because the principles are not stated in a sufficiently formal manner to make satisfaction of them a completely objective affair. For example, Principle (4) concerning individuation of matter qua matter needs detailed analysis, but very much along the lines already given in Section 2.

Reconstruction of the concept of matter along the lines of the formal definition just given does not, however, do justice to what is probably the most important insight of Aristotle concerning the concept of matter. This is the relative sense in which bricks, for example, are the matter of a house, and clay, the matter of bricks. As things have turned out the relative sense of matter has not become a fundamental concept in modern science, but its practical importance in science as well as in ordinary affairs is easily recognized. Biologists, for instance, almost always use such a relative concept of matter, even if it is not so labeled. A more systematic and explicit analysis of the way in which the relative concept of matter can or does enter in various modern theories of science would seem desirable.

## NOTES

* The first draft of this paper was commented upon by Michael Frede, and I have made several needed revisions in the light of his remarks, even though we remain apart on a number of questions of central importance.

1 Aquinas, in the *Treatise on Separate Substances*, takes the firm position that the heavenly bodies have both form and matter.

2 References refer to Parts and Articles of Descartes's *Principia*.

3 This Scholastic notion of virtualness is hard to give empirical content. Typical examples of another sort help illustrate its meaning: a pentagon virtually contains a quadrangle and a quadrangle virtually contains a triangle; a man is virtually an animal, and an animal is virtually a plant.

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