SCIENCE

THE MECHANIZATION OF THE WORLD PICTURE

E. J. Dijksterhuis

Translated by C. Dikshoorn

This work, by one of the most profound interpreters of the history of mathematics and mechanics, was already a classic at the time of its first appearance in English in 1961. It presents a detailed account of the origins and development of the physical sciences, including chemistry and astronomy, from the Pythagoreans of antiquity through the Middle Ages to the classical physicists of the seventeenth century, in whose crowning achievements the mechanistic world picture was finally realized. The core of the book covers the century and a half that began with Copernicus and culminated in Newton. In an epilogue the author seeks to clarify the meaning of the term "mechanistic" as applied to the scientist's concept of the physical world. He examines and rejects a number of ways of interpreting Newtonian science, and suggests a definition that highlights the differences between medieval and early modern "mechanics" and mathematical concepts. The interplay of science and philosophy receives throughout a full and lucid discussion.

"... this great work steps straight from the printing press into the shelves of standard and authoritative works ... it will be a continual work of reference for many years to come."
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"... no other single volume makes so clear the relationships of ancient and medieval science and philosophy to the development of modern physical science ..." *Science*

"... a mine of information that will be of great value to all serious students of the subject." *English Historical Review*

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perceives is appearance, thought may at least apprehend the reality underlying this appearance.

16. The repeatedly enunciated idea that the sensible world is nothing but a representation of an ideal reality, and that true being, actual being, cannot be apprehended by the senses, but only by the mind, is reflected completely and consistently in the *Timaeus*. The underlying idea of the dialogue is that a benevolent Demiurge has formed the universe from a chaos of primordial matter, as an image of an eternal world of forms which he constantly kept in mind during his work. The considerations that governed him were of a mathematical nature: the fact that between the elements earth and fire, which were to guarantee the tangibility and visibility of his creation, two more elements, namely water and air, had to be introduced, was the necessary consequence of the mathematical truth that between two cubic numbers, a^3 and b^3 (and cubic they had to be, because the object was the creation of a three-dimensional universe), there can be found two mean proportionals, i.e. two terms forming with the two original terms a geometric progression (a^3, a^2b, ab^2, b^3). According to a train of thought in which the connexion with physics as well as rational mathematics is temporarily abandoned, and which pertains entirely to the sphere of numerology, the mathematically constructed musical scale furnishes the material for two circular motions in the sky, one of which causes the diurnal revolution of the celestial sphere about its axis, while the other determines the oppositely directed proper motions of the planets along or parallel to the ecliptic; primordial matter itself is finally found to be identical with geometric space, and the smallest particles of the elements are due to the fact that parts of that space are bounded by four out of the five regular polyhedra (then a recent discovery of youthful and rapidly developing Greek mathematical science).

17. This is a further example—this time from mathematical imagination—of the evolution of a corpuscular theory of matter related to that of Democritus. Here, too, the corpuscles are limited parts of a primordial matter which is without qualities or, if this is preferred, invested only with the quality of extension in space and the impenetrability assumed to result therefrom. The two theories also resemble each other in the way in which concrete physical phenomena are accounted for by means of these elementary corpuscles. On the other hand they differ fundamentally from each other in that Plato's corpuscles appear not to be indivisible. In fact, the polyhedra, by means of which they have been cut out of spatial matter, apparently are considered in themselves as composite structures, whose invariable building-elements—which might truly deserve to be called atoms—consist of two kinds of triangles, from which the faces of the polyhedra are built up: the right-angled isosceles triangle, four of which can be combined to form a square, so that 24 of them are required to form the cubic corpuscles of the element earth; and the right-angled triangle with angles

of 30° and 60°, six of which go to make an equilateral triangle, so that 24 of them are required for a tetrahedral fire-particle, 48 for an octahedral air-particle, and 120 for an icosahedral water-particle. The various elementary corpuscles may break up into these constituent triangles, and these again may be combined into polyhedra. From earth only earth can naturally be formed again, but an air-particle may change into two fire-particles and vice versa, while on account of the relation $120 = 2 \times 48 + 24$ a water-particle may change into or arise from two air-particles and one fire-particle.

18. These changes—transmutations in a mathematical chemistry of elements—are apparently imagined to take place with thin triangular laminae of matter, out of which physical models of regular polyhedra might be constructed, rather than with ideal spatial forms, which after all do not permit of such manual handling. Thus the story of the *Timaeus* vacillates continually on the border-line between mathematics and physics, between the realm of pure thought and that of natural things, between myth and empirical reality, between fancy and fact. It is perfectly natural that a present-day reader, accustomed as he is to the rigorous mental discipline of modern science, should feel bewildered and lose patience, but if he wants to know how physical science has evolved, he cannot afford to neglect the *Timaeus*: in some periods it was thought to contain the supreme knowledge about nature.

But the whole spirit of the *Timaeus* is diametrically opposed to that of the Atomists' world-picture. Whereas in their view both the genesis of the universe and the events taking place in it remained subject to blind chance, in the *Timaeus* a benevolent and wise Demiurge transforms a chaos into an orderly cosmos; whereas the Atomists regarded the life of gods and men as a special variety of the universal mobility of the atoms, Plato makes the cosmos a living being by investing the world-body with a world-soul; whereas the Atomists had no answer to the problems of the existence and purpose of the universe, the *Timaeus* accounts for both: the goodness of the Demiurge would not let Him allow Chaos to persist in the state of disorder in which He found it, and induced Him to transform chaotic spatial matter into a fair whole, which was to be as like Himself as possible.

E. ARISTOTELIANISM[8]

19. A discussion of Aristotle's views on natural philosophy or science entails the fundamental methodological difficulty that his own system can no longer be disentangled from the expositions and accretions due to his ancient commentators and Scholasticism. He is always extremely terse in his formulations, and often obscure; not infrequently the same term is used to signify different ideas. His works were therefore in great need of commentary, but this led to constant differences of opinion about his true meaning, with the result that frequently this meaning can no longer be

dissociated from the interpretation. The following short summary of some important points of his doctrine is intended to deal only with what is by common consent regarded as genuinely Aristotelian.

A second difficulty is that the whole of Aristotle's philosophy is so closely interwoven that it is hardly possible to explain a few details apart from their context. The philosophical system as a whole, however, is outside the scope of this work, and we must confine ourselves to what is strictly necessary for the understanding of the development of science—namely the following points:

a. The doctrine of substance and accident, matter and form, potentiality and actuality.
b. The concept of motion.
c. The doctrine of the elements and the theory of *mixtio.*
d. Natural and enforced motions.
e. The general world-picture.
f. The concept of place and the impossibility of the void.
g. The doctrine of the four causes and the concept of purpose.
h. The general theory of knowledge.

20. To begin with, however, Aristotle's relationship to earlier thinkers must be made clear: he differed from them fundamentally in three different ways.

Firstly, he opposed Platonism by radically rejecting the view that true being is to be found in a transcendental world of forms. The subject of philosophy in general and that of science in particular is formed by the things we perceive by the senses; all knowledge we can acquire of them ultimately originates in sense-perceptions, even though the mind has its own active function to fulfil in the elaboration of these data; this view leads to a fundamentally empirical attitude towards the phenomena of nature.

Secondly, in framing his scientific theories he adopted a course that was in complete contrast with that chosen by the Atomists. Indeed, the chief aim of the latter had been to use only such explanatory principles as admit of quantitative determination: extension in space, geometrical form, position, arrangement, motion. Aristotle, on the contrary, wished to evolve a physical science of qualities, in which material bearers of properties were therefore regarded as explanatory principles.

Thirdly, he repudiated altogether the fundamental proposition of Eleaticism, that being was not subject to generation, change, and corruption. In contrast to the argument of Parmenides, that being cannot arise either from being (which is already, and consequently does not arise) or from not-being (because a thing cannot arise from something that is not), Aristotle pointed out—and this is always the method by which he tackled his problems—that several meanings of the word 'being' have to be distinguished, and that it is quite possible to make the changes we observe in

nature intelligible by a deeper analysis of the concept of being. This possibility will be considered in the following discussion of the first of the points enumerated above.

a. *Substance and Accident, Matter and Form, Potentiality and Actuality*

21. Substance in the primary and strict sense of the word denotes the being of every concrete, individually existing thing: Socrates, this table, this statue. It is the first and most fundamental mode of being or category, which on this account is essentially distinct from the nine others (including quality, quantity, place, and relation), all of which express accidental modes of being. This term accidental or secondary is not to be taken in the sense of insignificant or inessential, and even less: casual; it is only meant to convey that the being of the accidents is not, like that of the substance, an *esse per se*, an independent being, but an *esse per aliud*, a being conditioned by something else. The accidents are inherent in the substance; thus, for example, the accidents of the substance Socrates are his being an Athenian (quality), his stature (quantity), his being in the ἀγορά (place), and his being a son of Sophroniscus (relation).

With every substance the analytical mind can distinguish between the sum total of the properties making this thing what it is, and that which by its properties is made into this particular thing. The first, conceived not so much as a mere aggregate of characteristics, but rather as an internal structure-defining principle, is called the form of the thing; the second, which expresses the possibility of acquiring a certain structure, is called the matter of it (in the strict sense of the word, which is expressed by the term *prima materia*). Form and matter are obviously distinguished only by thought; they do not exist as separate and independent entities, whose union by a kind of chemical combination constitutes the thing. Aristotle does say that form is imposed on matter or impressed in it, and (later) that matter is 'informed', but this metaphor should not tempt us to regard form and matter themselves as substances, to substantialize, hypostatize, or materialize them.

22. The term 'matter', however, may also be applied in a less strict sense. When (to quote the classic Aristotelian example) a sculptor makes a statue from a piece of marble, he imparts to the block of stone a set of properties, a form (including the external shape), which make of it this particular statue. Now it can be said in the figurative, relative sense that the block of marble was the matter which has been stamped as a statue by this form. It is obvious that the block of marble is not to be called matter in the absolute sense, that it is not *prima materia*, for it already had a form before the sculptor started on his work: it had a colour, dimensions, a place, and, above all, it was marble. It is therefore to be distinguished as formed or informed matter (later also called *materia signata*) from the *prima materia*. In other words, the *prima materia* stands in the same relationship

to the form-determining principle in a thing as the *materia signata* in the statue to the form imparted to it by the sculptor. It is, as it were, the limit to which the thing approximates when by thinking about it we strip it of more and more of its properties.

Form thus makes matter into substance. For the being of the substance, however, not all the properties jointly constituting its form are equally important: some are indispensable, for example the way the material in a block of marble is composed of the elements, while others, such as the degree of heat or the place, might be changed without the substance ceasing to be marble. The first group, that of essential properties, is denoted by the name of substantial form or mode of being; the second, that of the secondary or accidental properties, by the name of accidental form. Form is thus called substantial in so far as it is indispensable to the being of the substance, and accidental in so far as it might also be different for this same substance.

23. A feature no less essential to Aristotelian philosophy than the distinction between matter and form is that between potential and actual being, more briefly between potentiality and actuality, which makes it possible to evade the Eleatic dilemma, from which the impossibility of becoming seemed to follow. From the block of marble a statue could be hewn, from a heap of sand this would be impossible; an acorn can grow into an oak, but not into a beech tree. Now in this possibility of becoming something Aristotle already sees in a certain sense the being of that something: the block of marble is potentially the statue that may be formed from it, and the acorn is the oak that may grow from it. The statue, however, will not exist actually (in reality) until the sculptor has finished his work; the acorn will not actually have grown into an oak until the process of growth is complete. Potentiality has then become actuality. To put it briefly, a thing is potentially what it may become, it is actually what it is.

A closer study of the matter shows that these two examples of potential being are not entirely equivalent. The block of marble lends itself to the object pursued by the sculptor; in the acorn, however, an active germinating capacity is present, which is the active cause of the generation of the oak. This difference induced commentators to make a distinction between *potentia passiva* and *potentia activa*.

Finally it will be evident without any further discussion that purely potential being belongs only to the *prima materia*; consequently this can have no independent existence; no single possibility has yet been realized in it. The *materia signata* on the other hand already leads an actual existence; it already has a form.

b. *The Concept of Motion*

24. To the very specific conception of being which is characteristic of the Aristotelian system corresponds an equally peculiar definition of the concept of motion. Indeed, motion in the most general sense of the word is the term used to denote any transition from potential to actual being, no matter whether in this process a substantial form is called into being (*generatio*) or decays (*corruptio*), whether the qualities of a thing alter (*alteratio*), whether it undergoes changes in bulk or quantity (*augmentatio* and *diminutio*), or whether it is going to occupy a different place (*motus localis*). It is more especially the last three kinds of changes—which are all of an accidental nature and take up a certain time—which are styled motion, while *generatio* and *corruptio*, which take place *in instanti*, are distinguished from the other three as substantial change or *mutatio*.

The wide scope of the Aristotelian concept of motion makes us truly understand the later scholastic adage: *ignorato motu ignoratur natura* (who knows not motion, knows not nature). This does not imply a kinetic world-picture in the later sense of the word (explanation of all natural phenomena by the motion of corpuscles), but it formulates the view that all natural events consist in a transition from potentiality to actuality, that change is the completion of the 'way towards form'. And thus it states emphatically—in contrast with all philosophical trends of an Eleatic character, which only acknowledge a science of the immutable—that the subject-matter of science is change.

25. The definition of motion as transition from potentiality to actuality, or as the way towards form, naturally is unsatisfactory in that it already employs the concept of local motion figuratively in its formulation. The original Aristotelian definition avoids this; it reads: motion is the actuality of that which *is* potentially, viewed from the standpoint of potential being (*motus est actus entis in potentia secundum quod in potentia est*) (see further I: 48), the latter addition probably being meant to convey that we do not speak of motion until a virtual reference is made to passive potentiality, suitability, or serviceability, or until active potentiality, the germinating capacity, actually manifests itself. Thus beams and bricks are indeed potentially a house, but there is a question of the motion of 'constructing' only when their suitability to form a house is turned to account in actual fact, not as long as they lie idle on the building-site.

Notwithstanding this wide conception of motion it can be said that local motion, i.e. change of place, already possesses in the Aristotelian system something of the predominant position it is later to take in physics; this is because it forms the basis of all the other kinds of motion. Quantitative change of a body is due to addition or removal of parts or to expansion or contraction of the body itself; qualitative and substantial changes cannot take place in any other way than in consequence of a meeting in space of an agent that causes the change with the thing in which the change is brought about.

The concept of local motion or change of place within time naturally calls first for a discussion of the concepts of place and time; the former will be referred to in I: 45.

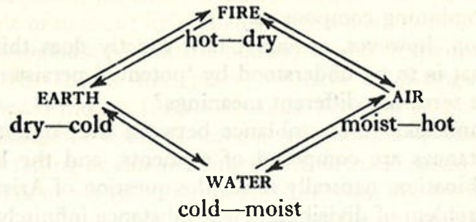
c. *The Doctrine of the Elements and the Theory of* Mixtio

26. It is not only through the distinction between matter and form, and between potentiality and actuality, that the Stagirite has left his mark on science for many centuries, but also because of the essential place accorded in his system to the Empedoclean doctrine of the four elements and the way he founded it on deeper principles. In accordance with the general tendency of his thought towards the qualitative, he seeks these principles among the qualities; for this they have to satisfy three requirements: 1, they must be haptic, i.e. affect the sense of touch; 2, they must be active, i.e. susceptible of causing qualitative changes; 3, they must form pairs of opposites. Now Aristotle knows seven such pairs of contrasting haptic qualities: hot—cold, moist—dry, heavy—light, dense—rare, rough—smooth, hard—soft, and tough—brittle (of which the last pair is often omitted). Among these the activity requirement is satisfied only by the first two pairs: a body which in itself is hot, cold, moist, or dry can transmit these qualities to another body, with which it comes into contact, but a rough or hard body does not make another body which it touches rough or hard as well. Now the elements of the material world are characterized by the four possible combinations of two of the fundamental haptic active qualities (which are sometimes also called the first qualities, *primae qualitates*). Thus the element

earth is dry and cold
water is cold and moist
air is moist and hot
fire is hot and dry.

It is always the first of the two qualities which predominates. In passing it may be observed that, in contrast with the above, the term active qualities is sometimes reserved for hot and cold, while the other two *primae qualitates* are called passive; moreover, the four elements never occur in the pure state: all substances in nature, even those bearing the names of the elements, are composed of at least two of the four, though one of them may greatly predominate. Thus in solid bodies with a high specific gravity, the element earth predominates; in all metals the presence of water has to be assumed, in order to account for their fusibility; smoke consists of fire and earth, &c.

27. The elements are not immutable; any one of them may be transformed into any other, owing to a fundamental quality turning into its opposite or both qualities doing so. The transformation, however, takes place most readily between two elements having one quality in common (the *qualitas symbola*); thus earth is transformed into water when dryness changes into moistness. The transformations, therefore, proceed preferably according to the following scheme:



but transformations of earth into air, and of water into fire, are not excluded.

Here another essential difference from Atomism becomes apparent; according to the latter theory the ultimate constituent elements were altogether immutable, whereas here the qualitative mutability, which is observed in the macrocosm and which Atomism wants to reduce to quantitative changes in the microcosm, is postulated as such for the microcosm as well.

From the Aristotelian doctrine of the mutability of the elements it is sometimes concluded that the elements proper are not therefore earth, water, air, and fire, but the first four qualities, and some of Aristotle's own utterances do indeed countenance this view. It is, however, liable to the objection that the elements are then no longer substances, but forms which in pairs make the *prima materia* into elements in the original sense of the word.

28. The assertion that all homogeneous substances known from experience are composed of the elements naturally raises the question of the mode of being to be assigned to the elements in such a compound (*μίξις, mixtio*). A homogeneous substance, not a mechanical mixture (*σύνθεσις*), in which a sufficiently acute power of vision would be able to detect the heterogeneous constituents lying side by side, can have only one substantial form, which cannot be the same as that of one of the four elements. It would seem, therefore, that in the compound the elements are no longer present, and it is indeed possible to quote passages which seem to support this view. On closer consideration, however, the matter appears less simple. In Scholasticism, therefore, the problem whether the elements do or do not persist in the compound is a moot point, for which the advocates of different possibilities all cite certain texts of Aristotle (II: 132–6). It is of course indisputable that the elements are potentially present and, in the strict sense of the word, not actually present in the compound, i.e. they may arise from it again, but they are not present in it unchanged, with their own substantial form.

A compound, therefore, can only come into being because the components undergo an internal change which predisposes them, as it were, to persist in a modified form in the newly arising substance. This is expressed by the Aristotelian formula: *Ἡ δὲ μίξις τῶν μικτῶν ἀλλοιωθέντων ἕνωσις*[9]

(*Mixtio est miscibilium alteratorum unio*: Combination is the union of the altered and combining components).

The question, however, remains: how exactly does this process take place, and what is to be understood by 'potential persistence', for as we have seen, the term has different meanings?

29. The unmistakable resemblance between the Aristotelian doctrine that the substances are composed of elements, and the later theory of chemical combination, naturally raises the question of Aristotle's attitude towards the problem of divisibility: is a substance infinitely divisible into ever smaller parts, which nevertheless retain the specific properties of the substance, or is there a moment at which further division is no longer possible if the substantial form is to be preserved? On this point again it is difficult to ascertain his opinion unambiguously. There are some passages where he may be assumed to refer to infinite divisibility (that is to say: potentially infinite, for there can be no question of actual infinity in Aristotle), and this would agree very well with his critical attitude towards Atomism; but elsewhere he argues against Anaxagoras that divisibility is subject to a natural limit, which could not be exceeded without impairing the substantial form. Each substance is thus assumed to possess its own characteristic smallest particles, its *minima naturalia*, which might be compared to the molecules of later chemistry.[10]

The argument adduced against Anaxagoras, however, relates in particular to constituents of living beings, in this case to flesh and bone, and it is doubtful whether the assertion made with regard to the latter may be extended; in other words, whether it is justifiable, in the context of Aristotle's thought, to speak also of the *minima naturalia* of the substances of inanimate nature, e.g. of the metals. But what was still doubtful in his own writings, ceased to be so during the subsequent development of his ideas in the work of his commentators. Already his Greek interpreters were agreed that every substance possesses its own *minima naturalia*, the size of which is characteristic of that particular substance (see the discussion of Scholasticism in II: 137).

d. *Natural and Enforced Motions*[11]

30. In contrast with Atomism, in which the perpetual motion of the atoms was postulated without the need for a causal explanation being felt, Aristotelian physics is based on the axiom that every motion (*motus*) presupposes a mover (*motor*): *omne quod movetur ab alio movetur*[12] (all that moves is moved by something else). This *motor* must either be present in the *mobile* (moving body) or be in direct contact with it; *actio in distans* (action at a distance) is excluded as inconceivable; a *motor* must always be a *motor conjunctus* (connected with the *mobile*).

It is, however, frequently a difficult problem to trace this *motor*. If we confine ourselves to local motion, no difficulties are presented by living

beings: the *anima* (soul), which is the vital principle, is at the same time the required principle of motion; living beings move *a se*, by their own efforts. For the *corpora inanimata* (inanimate bodies), however, the question is not so easily answered. In the first place, we have to distinguish between natural and enforced motion (*motus secundum naturam* or *motus naturalis*; *motus praeter naturam* or *motus violentus*). An example of the first kind of motion is a stone falling or smoke rising in the air; the second occurs when a stone is thrown or an arrow is shot in any direction. We are here entering the important field of the phenomena connected with falling bodies and projectiles, which already occupied a prominent place in Aristotelian physics and which later was to be of fundamental importance for the rise of classical science.

The phenomenon of spontaneous falling which some bodies exhibit when released, and the equally spontaneous rising of others (smoke, flames), which may be termed 'falling upward', was naturally associated from ancient times with the qualities heavy and light, which are perceived if the upward or downward fall is impeded. These qualities must naturally be connected in some way or other with the first qualities from which the elements are derived; the Ancients, however, never succeeded in understanding this connexion ontologically (in its essence); they could merely establish phenomenologically (by description), on the basis of their experience of *mixta* (composite bodies) in which either of the elements earth or fire preponderates, that these two *elementa extrema* are heavy or light, as the case may be, under all circumstances; the other two, the *elementa media*, may behave variously and are accordingly styled heavy-and-light or relatively heavy or light: water may place itself above solid bodies, but will fall down in the air; it is therefore light as compared with earth and heavy as compared with air. Since, however, the two *elementa media* as a rule function precisely as media for falling bodies (which is not possible for earth and fire), the discussion may further be confined to the motions of bodies which consist completely or predominantly of earth or fire and move in water or air; it is generally in this way that the terms 'heavy bodies' and 'light bodies' (*gravia* and *levia*) have to be understood.

The fact that a *grave* falls downwards, i.e. towards the centre of the universe, and a *leve* upwards, i.e. towards the lunar sphere, may also be formulated by saying that according to the order of the cosmos the former appears to have its natural place at the centre, the latter at the periphery, and that they immediately move in that direction if they are not impeded. The perfectly realized natural order, with respect to which all bodies are constantly in active potentiality, would therefore consist in the four elements filling up the space within the lunar sphere in concentric spherical layers, earth directly about the centre, then water, then air, and finally fire.

31. The phenomenon of falling bodies (we now refer only to the downward fall of *gravia*, but the whole argument also applies, *mutatis mutandis*,

to the *levia* in their natural upward motion) now raises three important questions: 1. What is the *aliud* (the something else) which sets and keeps a falling body going? 2. How is it that one body falls a given distance in a shorter time than another? 3. What is the cause of the acceleration of falling bodies? These are questions of such fundamental importance for the rise of classical physics that it may be said to have evolved largely from the attempt to answer them; there can be no better way of understanding the difference in character between ancient and classical science than by first seeing what Aristotle has to say on these questions.

The first question is not a little embarrassing both to him and to his ancient and medieval commentators. Since *corpora inanimata* are concerned, motion *a se* is excluded; since, again, the idea of an *actio in distans* has from the first been ruled out as inconceivable, the *simul esse* (immediate contact) of *motor* and *mobile* being regarded as a self-evident requirement, no single explanation can be considered which inclines towards the supposition of attraction exerted by the natural place or the bodies there present.

In accordance with an interpretation current among Scholastics the question was finally answered that as *motor* the *generans* is indicated, i.e. the cause, whatever this may be, which at one time gave rise to the *grave*, which impressed its substantial form on matter, and thus also called into existence all the associated *accidentia*. This *generans*, however, can only be an *agens remotum* (remote agent); the substantial form is *agens proximum* (immediate agent); but a substantial form can act only through the associated qualities and capacities; the function of *agens instrumentale* (instrumental agent) is now performed by the accident *gravitas* (gravity), through which the body is potentially in its natural place about the centre. In order, however, that the fall may actually occur, the *impedimentum* (the impediment in the form of a support or a cord on which the *grave* is suspended), which first prevented the falling of the body, has to be removed; the *removens impedimentum* (that which removes the impediment) thus acts as *motor accidentalis*.

This, however, does not solve the problem of what acts as *motor conjunctus* during the fall. Aristotle does not make any unambiguous statement about this, and Scholasticism therefore had to study this problem anew. It will be seen later (II: 109 et seq.) what different views have been expressed about it.

32. The second of the above-mentioned questions, namely how it is that not all bodies in falling have the same velocity, is nowhere explicitly dealt with by Aristotle, but his opinion may be inferred from several passages in which he refers to this phenomenon in the course of other arguments. Relying apparently on the universal validity of certain non-deliberately acquired experiences (a leaf slowly fluttering to the ground, as compared with the falling of a stone; the retarding of the fall when it

takes place in a liquid instead of in air), he assumes that the velocity of the falling body (i.e. the average velocity over a given distance) is proportional to the weight of the falling body and inversely proportional to the density of the medium. It is uncertain whether he wished this proportionality to be considered strictly valid in all cases, i.e. whether he would have accepted the conclusion frequently attributed to him afterwards, that a body ten times heavier than another body would have to travel the same distance in the same medium in one-tenth of the time; indeed, in another (similar) case he appears to consider his proportion as valid only within certain limits.

33. Finally, it is difficult to ascertain in what way he accounted for the fact—again familiar to him from everyday observation—that the velocity of a *grave* (the term 'velocity' taken in the sense of velocity at a particular moment, or instantaneous velocity) increases during the fall. When he wants to prove that a natural rectilinear fall could not continue indefinitely, he argues that in this case the velocity, and accordingly the weight of the body, would have to increase beyond all proportion; on this account he has sometimes been supposed to hold that the weight increases as the body approaches the natural place. Shortly before this, however, he emphatically denies that so external a circumstance as distance from something else could have any influence, since the substantial form of the *grave* after all does not change. This statement in itself is typical: it is not their relations to other things which determine the vicissitudes of material bodies, but their own character, their nature.

34. The vagueness and uncertainty of Aristotle's answers to the fundamental problems of falling bodies can undoubtedly be attributed to the fact that their motion proceeds by nature, spontaneously; such behaviour does not cry out for explanation in quite the same way as behaviour which appears to be contrary to the nature of a particular body, as is the case with a stone thrown upwards or sideways. Then it is imperative to explain the *motor conjunctus*, as the body's own nature can no longer serve as an explanation. What is it, then, that still propels the *projectum* (the body thrown) onwards when it has left the hand of the *projector* (thrower) and therefore has become a *projectum separatum* (projectile, separate from the thrower)? The answer to this question, which appears to form one of the most curious features of Aristotelian physics, is as follows: while a body is being thrown, the *projector* is at first still in contact with it, and so he himself functions as *motor conjunctus*. During this period he sets the adjacent layer of the medium in motion, together with the *projectum*, but—and this is the essential point—he also imparts to it a *virtus movens*, a power to set something else in motion; he transfers his *projector*'s function to that layer of the medium. And this layer, during the next period, then repeats the action of the original *projector* during the first period: it sets the *projectum* in motion and transfers motion as well as *virtus movens* to the next layer.

Thus in every point of its path the *projectum* finds the *motor conjunctus* that is required for maintaining the motion. The moving power, however, is somewhat weakened with every transfer; a moment will arrive when the next layer of the medium is still set in motion but no longer acquires a *virtus movens*. The *projectum* now proceeds to perform its natural motion, and the layer of the medium last set in motion comes to rest, together with the last but one.

This complicated theory has often been misunderstood in the sense that the *projector* was represented as setting the medium in motion, the latter then carrying the *projectum* along with it as in an accidental (dragging) motion. Aristotle, however, rejects this notion as emphatically as the explanation—already known in his days—which uses the theory of *antiperistasis*; according to this, the air forcing the *projectum* ahead plunges into the void left by its motion and thus impels it yet further.

35. Besides the *motus violentus* of the *projecta separata*, Aristotle also considered the case of enforced motion, in which a *mobile* is drawn or pushed along; a vehicle on a road, for example, or a vessel in water. In this case there is naturally no problem concerning the *motor conjunctus*; it is seen operating. The propositions about these motions enunciated by Aristotle, in a very explicit formulation, have also fulfilled a very important function in the development of science; indeed, by force of circumstance almost every idea of the Stagirite, irrespective of its intrinsic value, has been an influential factor in the history of thought.

Again it is the most commonplace experience that he lays down in his propositions: a vehicle or vessel moves the more rapidly according as it is pushed or drawn with greater force, and, the exertion being equal, the more slowly in proportion to its weight. The motion is evidently uniform as long as the force does not change. This may be summed up in what may be called the fundamental law of Aristotelian dynamics and the historical counterpart of the fundamental law of motion of classical dynamics: a constant force imparts to the body on which it acts a uniform motion, the velocity of which is directly proportional to the force and inversely proportional to the weight of the body.

In present-day thought it appears self-evident to regard the above-mentioned law of falling bodies, which relates the (average) velocity to the weight of the falling body and the density of the medium, as a particular case of this general dynamic law. It does not seem, however, that Aristotle would ever have done so, and once the modern reader has entered into the ancient mode of thinking, he will find this quite comprehensible. If weight is regarded not as a force exerted from the outside on the *grave*, but as an intrinsic principle of motion which is closely connected with the nature of the body, and if, moreover, the natural character of the motion it causes is stressed, it must seem almost impossible to consider it as a particular instance of an external *motor conjunctus*, which causes an enforced motion,

i.e. a motion not resulting from the character of the *mobile*. The more so because the function of weight in the two motions seems to be altogether different: heavy bodies will fall readily, but a heavy vehicle is hard to set in motion; weight here appears to counteract the pushing or pulling force.

In actual fact it obviously does not do so; in the motion of a vehicle on a horizontal road weight as such cannot play a direct part; the body need not be carried, and its weight comes into play only indirectly, because the friction depends on it. What is actually involved is inertia, the tendency to remain at rest, which is indeed proportional in intensity to the weight, but by no means identical with it in essence. Many centuries were to elapse before this complicated relationship was to be understood, before men learned to distinguish between inertia and gravity, between mass and weight, and in particular before they were to discover that the tendency to persist in the state once entered upon, which is called inertia, relates equally to the state of motion and the state of rest. Persistence in a state of motion as long as it is not disturbed by external causes was, however, altogether beyond the horizon of Aristotelian physics: *omne quod movetur ab alio movetur*; and when this *aliud* is absent, when the soul leaves the living body, the substantial form of a *grave* disappears, the layers of the air lose their *virtus movendi*, or the *motor conjunctus* of a vehicle stops functioning, the motion is immediately at an end. *Cessante causa cessat effectus*: with the cause the effect ceases.

When in the fundamental law of dynamics we read 'inertia' instead of 'weight'—which is no doubt in accordance with Aristotle's deeper intentions, though not with his actual words—and take 'inertia' in the sense of resistance to the disturbance of the state of rest, and if we (while fully aware of the anachronism we are committing) formulate the law symbolically as

$$v = f \times \frac{F}{I}$$

(in which F = moving force, I = inertia or power of resistance, v = velocity, f = constant of proportionality), the law of falling bodies, which may also be written

$$v = f \times \frac{W}{R}$$

(in which W = weight, R = resistance of the medium, v = average velocity), begins to look rather more like a particular case of the universal law. The connexion becomes even clearer when in the universal law we assume the resistance of the medium to be taken into account as well. It is true that Aristotle does not make any explicit statement about this, but it can hardly be doubted that, on the analogy of his views on falling bodies, he considered the velocity acquired by a vehicle under the influence of a given force to be inversely proportional to the resistance offered by the road on, or the medium in which the motion takes place. The universal law of dynamics would then be symbolized by

$$v = f \times \frac{F}{R} \quad \text{or} \quad F = f \times v \times R,$$

in which R (*vis resistiva*) includes all those influences which impede the motion, even if they seem as heterogeneous to our minds as inertia and friction.

36. With this definitive formulation of the fundamental law of Aristotelian dynamics, which is therefore the ancient analogue of the fundamental formula $F = ma$ of classical mechanics, we must make yet another reservation besides that required by the anachronism of the expression. In fact, the proposition holds only when $F > R$; the moving force must be able to overcome the resistance if motion is to be caused. While, therefore, to use an example given by Aristotle himself, a force A, which displaces a body B a given distance in a given time, will cause a body $\frac{1}{2}B$ to cover twice the distance in the same time, it is by no means certain that it will move a body $2B$ half the distance in the same time. For this the force must first be able actually to displace the body $2B$.

In the above formulation of the fundamental law of dynamics a peculiarity of Aristotelian thought, which later seriously impeded the growth of classical mechanics, is clearly revealed, namely the tendency to divide the moving force by anything that may be considered as resistance, and never to subtract the latter from the former. All resistances are dealt with in the same way as the resistance of a conductor when the intensity of an electric current is calculated, and not in the way a frictional resistance in mechanics or a counter-voltage in electricity are taken into account. It will be seen presently what important consequences this involved for the question about the possibility of a void (I: 45).

37. We have discussed natural and enforced motion at great length, but the subject deserves to be dealt with in detail on account of its eminent significance for the adequate understanding of the Aristotelian view of nature and of the great effort that was needed to outgrow it. To this day every student of elementary physics has to struggle with the same errors and misconceptions which then had to be overcome, and on a reduced scale, in the teaching of this branch of knowledge in schools, history repeats itself every year. The reason is obvious: Aristotle merely formulated the most commonplace experiences in the matter of motion as universal scientific propositions, whereas classical mechanics, with its principle of inertia and its proportionality of force and acceleration, makes assertions which not only are never confirmed by everyday experience, but whose direct experimental verification is fundamentally impossible: one cannot indeed introduce a material point all by itself into an infinite void and then cause a force that is constant in direction and magnitude to act on it; it is not even possible to attach any rational meaning to this formulation. And of

all the experiments by means of which textbooks of mechanics are wont to prove the fundamental law of dynamics not a single one has ever been carried out in practice.

Aristotelian physics thus has the advantage over classical mechanics in that it deals with concrete, observable situations constantly encountered. But from a scientific point of view this very advantage constitutes its weakness, for these situations are so complicated (the reader need only think of a vehicle drawn through the air along a rough road, or of a body of any given form thrown upwards) that even with the aid of perfected classical mechanics they can be treated mathematically only by approximation and at the expense of comparatively arbitrary suppositions.

The theory of motion calls for just as extreme an idealization as that by means of which Euclidean geometry is deduced from physical experiences of solid bodies. The Aristotelian mode of thinking had to be supplemented by the Platonic to become truly fruitful. But this combination of the two great antique schools of thought, so indispensable for mechanics and thus for the whole of physics, was at first achieved to a very limited extent; antiquity only accomplished it for statics, and it was not until the seventeenth century that dynamics, too, could benefit from it.

38. For statics the desired idealization took place in the work *Quaestiones Mechanicae*, which used to be attributed to Aristotle and in any case originates from his school. In fact, this work contains discussions on the equilibrium of a lever, in which, instead of a physical bar with weights attached, a weightless line-segment is considered, which is acted on by forces that are directed vertically downwards. The remarkable feature of the discussion, however, consists in the striking relation that is established between the lever-principle and the fundamental law of peripatetic dynamics. It is required to be proved (Fig. 1) that if the lever is adapted to pivot about O and in the points A_1 and A_2 carries the weights W_1 and W_2, the condition of equilibrium is as follows:

$$W_1 : W_2 = OA_2 : OA_1.$$

In order to understand this, the author imagines the bar to pivot about O. A_1 and A_2 then describe circular arcs A_1B_1 and A_2B_2, the lengths of which are as OA_1 to OA_2. Since these motions take place in the same time, the velocities are in the same proportion as the distances, and therefore the relation formulated states that the product of weight and velocity has the same value for both bodies suspended on the lever. According to peripatetic dynamics, however, this product in general is a measure of the moving force for the motion of a body, and the condition imposed on the weights

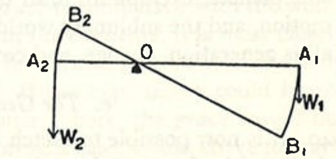


Fig. 1. Derivation of the lever-principle according to Aristotle.

thus states that they exert equal forces on the lever, so that no pivoting occurs.

The striking feature of this argument is that whereas in the law of dynamics the product of weight and velocity was a measure of the force which causes the motion of a body, it serves here to express the motive power of the body itself. It should be remembered, however, that each of the two bodies strives to set the other in motion and therefore functions as effort in relation to the other body considered as load. But the exertion required to move the load is now conditioned by the product of weight and velocity, and is obviously a measure of the ability of the effort to cause that motion. In any case this derivation, which is merely outlined in the *Quaestiones Mechanicae*, was afterwards generally taken in this sense. That the element of time, which is quite irrelevant, was brought in was evidently because it thus became possible to speak of velocity and to establish the connexion with dynamics.

Though the argument is not very convincing, this does not alter the fact that it contains the germ of a general principle which was afterwards to perform an important function in mechanics under the name of the principle of virtual displacements (or, by another name reminiscent of its origin, the principle of virtual velocities).

39. It has been shown above that the substantial form of an element determines the natural motion it can perform, and also that this motion is rectilinear for each of the four elements hitherto encountered. However, a non-rectilinear natural motion is also known from everyday experience, namely the circular motion of the heavenly bodies, and from this it follows that the latter cannot be composed of the terrestrial elements, earth, water, air, and fire. There must therefore be a fifth element, to which circular motion is by its nature to be ascribed, i.e. in virtue of its substantial form. Aristotle argues that this fifth element, the ether or the *quinta essentia*, has neither gravity nor levity, and that it is not liable to quantitative, qualitative, and substantial modifications; it can neither perish nor be transformed into one of the terrestrial elements. In this way a fundamental antithesis between earth and heaven has been established, between the world of stars and planets, exempt from all change other than continual local circular motion, and the sublunary world, where nothing lasting is to be found and all is generation, change, and corruption.

e. *The General World-Picture*[13]

40. It is now possible to sketch in broad outline the general picture which the Stagirite forms of the universe. This picture is essentially geocentric in character: the earth is situated motionless at the centre of the universe, and the heavens revolve steadily about an axis passing through that centre.

When Aristotle stated this proposition, he was naturally acquainted with the other possibilities for the structure of the universe which had been

considered by earlier thinkers. He undoubtedly knew the world-picture of Philolaus, in which the earth was conceived as revolving about a central fire (at least according to one of the suggested interpretations), and perhaps also that of Heraclides Ponticus, in which both an axial rotation and a circular revolution were ascribed to it. That he rejected these possibilities and established the supremacy of the geocentric world-picture for centuries to come is due to the totality of his doctrine. He was not a mathematical astronomer, who, responding to Plato's challenge to save the celestial phenomena, invented a system of motions which could account for the facts observed and who did not need to be concerned further with the problem whether this system could be made to agree with the nature of physical reality; he was a synthetic thinker, who aspired to create a philosophically justified integral world-picture, and who therefore could not study cosmology without relating it to physics nor divorce either from general philosophy.

Aristotle's conviction about the central position of the earth in the universe is therefore closely bound up with the other essential features of his system, particularly with the theory of natural motion and natural place, and consequently with the doctrine of the elements. The earth, because of its heaviness, cannot be placed anywhere but where it belongs by nature: at the centre of the universe, which is the natural place for what is heavy; even if at any time it should not have been at the centre, it would have been bound to reach it long ago in natural rectilinear motion (which because of the finiteness of the universe cannot be perpetual). Nor can it revolve about an axis at the centre of the universe, since circular motion does not fit in with the substantial form of any sublunary element. The diurnal motion of the heavens is not therefore a reflection of a rotation of the earth, but a genuine natural motion, resulting from the nature of the ether.

41. It is important to appreciate the logical relation existing between the geocentric theory and the theory of natural place. The former is a consequence of the latter, not its logical ground. That is to say: when we see a heavy body, which has been released, fall towards the earth, this does not happen because it is of the nature of the *grave* to unite itself with the whole to which, in virtue of its composition from the elements, it is most closely related, but because the earth contains the natural place where the body belongs on account of that composition. If the experiment could be repeated with the earth removed to the lunar sphere, the *grave* would not fall towards the earth, but, just as in the present case, would strive to reach the centre of the universe, which is its natural place; it does so *per essentiam*, when it falls towards the earth this is *per accidens*.

If we now imagine, as before, the prevalent chaos in the sublunary world replaced by the perfectly orderly disposition of the elements according to heaviness and lightness, the following picture arises: round the centrally situated, spherical earth are eleven spheres (i.e. solids which are bounded by two concentric spherical surfaces), the three innermost of which, successively containing the elements water, air, and fire, are at rest, whereas the eight outermost spheres, which successively carry the planets Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn, and the system of the fixed stars, revolve daily about the axis of the heavens. However, the true facts have not yet been described, for the planets owe their very name 'planet' to the fact that they move, each with a period of its own, in relation to the stars, and therefore in each of the seven planetary spheres other motions must take place, which are the cause of these movements.

42. With regard to this fine-structure of the planetary system Aristotle concurs with the theory developed by the mathematician Eudoxus of Cnidus, which is known in the history of astronomy as the theory of concentric spheres. In this first attempt to satisfy Plato's demand to save the phenomena of planetary motion by means of a system of uniform circular motions, each of the planets Saturn, Jupiter, Mars, Venus, and Mercury is carried round by a group of four spheres, each subsequent sphere regularly sharing in the motion of the preceding one, the first bringing about the diurnal rotation, the second the proper motion along the zodiac, while the third and fourth cause the retrogradations in the orbits. Sun and Moon each perform three such revolutions: with the sun, one is required for the daily and one for the yearly motion, while the third has to save an imaginary motion in latitude; with the moon, the daily and the monthly motion, and the retrogradation of the line of nodes are thus successively caused. For the seven planets a total of $4+4+4+3+4+4+3 = 26$ spheres is accordingly required, to which the sphere of the fixed stars has to be added as the 27th. The axes of rotation and the periods of the various spheres had to be so chosen that the various phenomena to be saved could also be represented quantitatively; it can only be guessed from a hypothetical reconstruction how far the attempt was successful. It is, however, firmly established that Callippus, in order to obtain better agreement with observed facts, was obliged to increase the number of spheres for each of the planets Mars, Venus, Mercury by one, and give two additional spheres each to the Sun and Moon, so that he required 33 planetary spheres. Aristotle adopted this correction, but had to increase the number of spheres once again. In fact, he considered it necessary to prevent the motion of an outer sphere from being transmitted to the inner ones; this was attained by inserting a number of so-called 'unrolling' (i.e. counteracting) spheres, the number of which is each time one less than that of the preceding group (for the daily rotation may indeed be transferred inwards); this leads to the inclusion of 22 more spheres, thus bringing the total up to 55. According to a criticism by Sosigenes the object in view could have been obtained with 49 spheres.

The characteristic feature of this theory of concentric spheres, which distinguishes it fundamentally from a later Greek planetary theory (I: 69 et seq.), is that it recognizes no motions of heavenly bodies beyond revolutions about axes through the centre of the universe.

It is also worth noting that in a rough representation of the Aristotelian system of the universe the fine-structure of the planetary system was frequently disregarded, so that there were then only eight celestial spheres, seven for the planets and one (number eight) for the fixed stars. Afterwards other spheres were to be assumed beyond the eighth, while the total number naturally also increased when the spheres of the sublunary elements were added.

In the realm of mathematical astronomy Aristotle thus appears in all respects to have followed the road indicated by Plato and first trodden by Eudoxus. This agreement between the two most influential thinkers of Antiquity, who for the rest contradict each other on so many points, has had important consequences for the history of astronomy. The axiom of the uniformity and circularity of the motions of the heavenly bodies, which Plato had framed on mathematical and religious grounds, had been supported by Aristotle with physical arguments and made an essential part of his world-system; enunciated unanimously by two such authoritative thinkers, it was bound to appear beyond all doubt. Nor did astronomers venture to deviate from this view before the beginning of the seventeenth century, and even then they only undertook this most revolutionary of all changes in the ancient world-picture from sheer necessity.

43. In connexion with the general principle of Aristotelian philosophy, that every motion presupposes a *motor*, the question of what causes the revolutions of the celestial spheres naturally arises.

Aristotle does not follow Plato in his belief that the planets are living beings, gods, who move by their own efforts. On the ground of the perpetuity and immutability of the celestial motions he does, however, come to the conclusion that the movers of the planetary spheres must be immaterial substances which, being all actuality and wholly devoid of potentiality, cannot themselves be in motion; for the planets there are fifty-five of them.

Finally, for the motion of the eighth sphere, the existence of a supreme, immaterial Prime Mover is assumed. The Prime Mover, however, does not set this sphere in motion by doing something Himself; that would be contrary to the fact that He is *actus purus*, and thus has nothing left to realize; perfect actuality must consist in absolute inactivity. However, He moves the eighth sphere, as the Aristotelian formula says, ὡς ἐρώμενον,[14] by being loved, i.e. the motion is the consequence of the affection in which He is held by the matter of the eighth sphere, of the craving for perfection that He arouses in it. This is in accordance with the general Aristotelian conception that matter aspires after form. It is not as passive as it may sometimes appear to be; the whole universe is pervaded by an aspiration after greater perfection, of which the Prime Mover is the ultimate aim. This aspiration causes a hierarchic arrangement of bodies (elements, minerals, plants, animals, man). It finds its consummation in man, because here matter is united with the most perfect form of which it is capable: the soul.

In the discussion of the immaterial movers of the celestial spheres, Aristotle's astronomy develops into what Plato's had been from the start: a rational theology, which informs us by rational means about the divine intelligences and their hierarchy.

44. For the better understanding of later developments in thought about nature an additional remark about the causal relationship between celestial motions and events in the sublunary world is called for. After what has been stated above (I: 39), on the absolute antithesis between the earth and the heavens, and in view of their distinct positions in the universe, it may appear as if such a relationship cannot exist. Yet this is not the case. In some way or other—the true situation should not be inquired into—terrestrial motions depend on celestial motions; the endless revolutions of the heavens call forth the equally restless rectilinear motions of the terrestrial elements, which underlie all generation, change, and corruption. It is true that these processes do not all take place in the same direction: there are generation and corruption, increase and decrease of quantity, strengthening and weakening of quality. And as contrary effects must have contrary causes, it cannot be the revolution of the eighth sphere alone which originates and maintains terrestrial motions; a second principle is required, and this consists of the motions of sun, moon, and planets—which are directed contrary to the daily revolution of the heavens—along the zodiac. The daily revolution is the cause of the perpetuity of sublunary processes, the passage along the zodiac the cause of their diversity. Thus everything that happens here is controlled from the celestial spheres.

In later times this conception was to become one of the strongest arguments in the justification of astrology. Aristotle himself does not draw from it any conclusion of a strictly astrological character, i.e. for the determination or prognostication of human character. It does become for him the starting-point for the adoption of the theory of the periodicity of world events, which had already been enunciated before his day and has never been forgotten since. When the Great Year, which is the least common multiple of all the periods of the celestial revolutions, is completed, everything in the sublunary world, together with all that is in the heavens, will return to its original condition. After this, everything will repeat itself, not only in the material but also in the spiritual sphere: the same natural phenomena will appear and the same philosophies will be enunciated. This periodicity must not, however, be understood in the sense of an alternate destruction and regeneration of the universe, such as Heraclitus and Empedocles had assumed and the Stoics were to believe later (I: 52); that would be contrary to the theory of the imperishability of celestial substances.

f. *The Concept of Place and the Impossibility of the Void*[15]

45. A subject of Aristotelian philosophy that is important in view of the later development of thought is formed by the discussion which was devoted by the Stagirite to the concept of place and which was to give rise to different localization theories.

He starts by defining the place of a body as the interior boundary of a body containing it (*ultimum continentis*): the place of the wine in a cask is the inside of the cask. This, however, at once leads to difficulties in connexion with the concept of local motion, which, as appears self-evident, is simply identified with change of place. In fact, a ship riding at anchor in flowing water would thus have to be in motion, because, being continually surrounded by different water, it is constantly in a different place. Descartes readily adopted this conclusion. Aristotle, however, rejected it and made his definition of place more precise: place is the first immobile boundary of the containing body, i.e. in the case of the ship in a river, the banks and the bed of the river.

The determination of the place of a body thus requires in the last resort an environment the immobility of which is firmly established; for sublunary bodies this is formed by the centre of the universe (to be understood as an immobile central body) and the interior of the lunar sphere (which indeed revolves, but in its entirety does not change its place). Difficulties will arise, however, when place in the heavens is to be determined, and more particularly when it is desired to localize the eighth sphere. Indeed, the latter is surrounded by nothing; there is not even a void outside it, for that would be something which, even if it does not contain any bodies, *might* contain them, whereas outside the universe, which forms the sum total of all material things, no body can exist; therefore the eighth sphere is not in a place, cannot consequently change its place, and yet must be continually moving.

Aristotle's localization theory here seems to be caught up in an insoluble contradiction. But the Stagirite was not to be discouraged; availing himself of a trick that was afterwards to be handled with great dexterity by the Scholastics, he introduces a *distinctio*: although in the proper sense the eighth sphere may not be in a place, in the improper sense (πώς) it *is*, and that is a sufficient argument to maintain its motion; each part of the sphere is surrounded by others, which together function as its place; the sphere as a whole is thus in a place *per accidens* (κατὰ συμβεβηκός).

So far no definite solution of the problem had been reached, for by causing the parts of the sphere that move along with it to function as its place, Aristotle had to sacrifice the feature of immobility. The problem of the localization of the eighth sphere, therefore, always remained one of the great stumbling-blocks in the way of the commentators of Antiquity and the Middle Ages. What the latter have said about it will be discussed later (II: 105 et seq.); as a preliminary a few brief statements have to be made about the attempts of ancient commentators to arrive at a more satisfactory solution.

46. Alexander of Aphrodisias recognizes that the eighth sphere is not in a place, but does not consider this an objection: the rotation of a sphere is not local motion, because the sphere as a whole does not change its place.

Themistius is of opinion that, although the place of a thing in general surrounds that thing, the eighth sphere may be localized from the inside. The place of the eighth sphere—likewise a place *per accidens*—is the sphere of Saturn.

Philoponus regards the whole localization concept in a manner altogether different from that of Aristotle. The place of all physical things is space with its three dimensions, which, though in actual fact it cannot be distinguished from the bodies occupying it (an actual void according to him is impossible), can be distinguished from them by thought just as well as matter from form. Space is immobile, both as a whole and in its parts, and thus satisfies Aristotle's requirement with regard to place. There exists a strict analogy between local motion and qualitative change: as soon as one body leaves a place, another comes to occupy it; as soon as one form perishes in matter, another takes its place. The view of Philoponus is, briefly, that place is the conceptual void.

A similar solution is that of Proclus, who identifies place with the light that fills the whole universe as the immobile One. At a later stage of physics these two theories were combined in a single one, in which the ether functions as localization medium.

Another remarkable theory is that of Damascius, who, on the analogy of Aristotle's definition of time as the number of a motion with respect to before and after, defines place as the set of geometrical magnitudes which determine the position of a body. Position here appears as an undefined concept, and Damascius does not attempt to elucidate it. Perhaps his line of thought may be paraphrased as follows: if an hour-glass or a clepsydra is running during a motion, each phase of the motion is associated with a number which indicates the quantity of water or sand that has run away since the beginning of the motion; this number is called the time; one may measure it without saying what motion is. Now consider a body at rest, and measure as many of its distances from the walls of the room in which it is placed as are sufficient to define the body. The aggregate of these numbers is called the place (τόπος, *locus*); one may determine it without saying what position (θέσις, *positio*) means.

A Greek physical scientist would have thought it too relativistic an idea to use an actual clock in measuring a length of time, and a defined frame of reference in determining a place. He conceived the true clock as an ideal hour-glass running from eternity to eternity, and for the determination of place took an ideal perpetually immobile environment. In order to find this,

we must imagine all bodies in the universe brought back into the place assigned to them by nature. Let all falling motions of heavy bodies and rising motions of light bodies have come to an end; let all the elements have arranged themselves in the four concentric spheres extending from the centre of the earth to the lunar sphere, then you will have the natural frame of reference for all determinations of place.

Within the eighth sphere we should therefore imagine, together with the real universe, also the ideal universe, in which everything is in its place. The place of a body in its actual position is now the set of magnitudes that determine its removal from its ideal position.

This theory is related to those of Philoponus and Proclus in so far that, in all three, two coincident spheres are assumed, one of which is the real, material universe; the other is, according to Philoponus, the void, according to Proclus, light, and according to Damascius, the ideally ordered universe.

Returning now to Aristotle himself, we shall discuss the important application of his concept of place to the question of the possibility of a void.

47. Aristotle passionately refuted such a possibility. This is not surprising; the supposition of the existence of a void, of the being of not-being as described by the Eleatics, formed the foundation of Atomism, and the Stagirite must no doubt have been very anxious to depreciate this system, which he must have violently disliked because of its materialistic tenor. He derives his first argument against it from the concept of place: a (limited) void would presuppose an environment in which bodies might indeed be placed, but in which nevertheless no bodies are present, a *locus sine corpore locato*, and that is a logical contradiction. A void is therefore inconceivable. It would have to be something in the nature of a thing that surpasses without anything being surpassed, a father without a child, a beverage that cannot be drunk, a feeling that cannot be felt.

To this logical argument Aristotle adds several more of a physical character. In a (boundless) void all possibility of determining a place or a direction is eliminated; no one point can be distinguished from another, no one direction can be preferred to another. A body, placed in such a void, for reasons of symmetry could never start moving; or once in motion it could never come to rest again, for why should it end its motion here rather than there? All these things are absolutely contrary to the Aristotelian conception of a limited universe, which in its immobile centre and its spherical enclosure—immutable as a whole—possesses the fixed frame of reference in relation to which the place and motion of bodies can be unambiguously defined. No reconciliation is possible between the idea of this limited universe with the definite structure of Aristotelian physics and that of the infinite homogeneous space of the mathematicians, in which the Atomists suppose the atoms to be introduced and to carry out their motions.

Still not satisfied with his arguments, Aristotle advanced fresh objections:

in a void there would be no resistance to motion, and thus, in view of the inverse proportion between the velocity and the density of the medium, the fall would have to proceed instantaneously, i.e. the falling body would have to reach the end-point at the same moment at which the fall starts. According to a proposition ascribed by Aristotle to the Atomists, all bodies would have to fall equally fast in this void, but how could this be reconciled with the proportionality between weight and velocity expressed in the law of falling bodies? And how could a body move when thrown if there is no medium that can act as *motor conjunctus*? And when finally the Atomists have to assume the existence of *vacua* between the atoms in order to account for the phenomena of condensation and rarefaction, and have to find space for the atomic motions in which, according to them, is the essence of all that the unprejudiced observer looks upon as generation, corruption, and qualitative change, the Stagirite challenges this necessity: his own conception of potentiality and actuality furnishes all the explanatory principles needed.

Although as a rule Aristotle speaks about the void without giving any further definition, his works contain the distinction that was to become customary later on, namely that between the so-called *vacuum intermixtum* or *disseminatum* (παρεσπαρμένον κενόν), which according to the Atomists is to be found between the atoms and which is therefore as impossible to observe as the atoms themselves, and the *vacuum coacervatum* (ἄθρουν κενόν), a space of finite or even infinite dimension, within which no atoms are supposed to be present at all. We shall use the words *microvacuum* and *macrovacuum* to make this distinction clear.

To Aristotle both are equally inconceivable. As we have seen, this opinion is based not on his establishment either of an internal contradiction in the atomistic doctrine or of the fact that its consequences are contrary to experience, but solely on the incompatibility of the opposed view with his own fundamentally different theories. The only exception is formed by the argument on the impossibility of any absolute determination of place and direction in an infinite homogeneous space. For the rest, the whole argument is emotional rather than logical in character, an expression of self-assertion rather than a refutation.

g. *The Doctrine of the Four Causes and the Concept of Purpose*

48. So far we have dealt in particular with those sides of Aristotle's system which are of special interest for the subject of this work. For this reason it was his physical, chemical, and astronomical theories that had to be considered, at the expense of the purely philosophical and biological aspects of his system. As a result a concept which occupies a prominent place in Aristotle's thought, the concept of purpose, has not so far been mentioned.

It is perhaps due to his vivid interest in animate nature, where he could constantly observe the efficient structure of the living organism, that the

concept of purpose is so prominent in his work, even when he deals with inanimate nature, from which it was later to be ousted altogether by more mechanistic views.

Nowhere does this become more apparent than in the discussion of the concept of cause, where he mentions not only the *causa materialis* (material cause; the matter from which a thing is formed), the *causa formalis* (formal cause; the form to be realized), and the *causa efficiens* (efficient cause; that which actually causes the event), but also the *causa finalis* (final cause; the purpose to be realized). The example of the statue illustrates this point too: the block of marble from which it is to be hewn is the material cause; the form which is present to the sculptor's mind during his work is the formal cause; the sculptor himself, through the intermediary of his tools, is the efficient cause; the destination of the completed statue is the final cause. Naturally the final cause may be identical with the formal cause when the sculptor is an advocate of '*l'art pour l'art*'.

It is obvious that the first three causes do not define the course of events in the universe unambiguously: they do not control and direct them; an olive might conceivably grow from an ear of corn. The first three causes correspond to the three aspects of a substance that can be distinguished as matter, form, and actualization of form (ἐνέργεια), but the fourth to the fact that the substance in virtue of its existence not only materializes a form but also implies the realization of a purpose. This aspect is indicated by the name ἐντελέχεια (entelechy), which is, however, often used indiscriminately with ἐνέργεια. This of course is not remarkable, considering the close relationship between formal and final cause (as a rule, realization of the form is at the same time realization of the purpose). Thus the original version of the definition of motion, given in I: 25 in the Latin translation: *motus est actus entis in potentia secundum quod in potentia est*, in one place[16] reads: Ἡ τοῦ δυνάμει ὄντος ἐντελέχεια, ᾗ τοιοῦτον, κινησίς ἐστιν and in another place:[17] τὴν τοῦ δυνάμει, ᾗ τοιοῦτον ἐστιν, ἐνέργειαν λέγω κίνησιν. The formula can be translated as: Motion is the realization of the form or the purpose of potential being, considered in its potentiality with regard to this form or its suitability for this purpose.

It is also observed that in the case of local motion formal and efficient cause may coincide: thus with falling bodies the tendency towards the natural place, which is inherent in the substantial form of the *grave*, is at the same time the *causa movens*. The natural place itself is the final cause.

h. *The General Theory of Knowledge*[18]

49. The influence that Aristotle has exercised on scientific thought is not entirely due to the study of his works on metaphysics, physics, and astronomy. In the collection of his writings on logic, which is usually called the *Organon*, there are general epistemological reflections on the requirements a demonstrative science should fulfil, and in fact during the renaissance of

scientific thought in the sixteenth and seventeenth centuries these ideas, instead of being confuted and rejected together with his ideas on nature, seem to have served precisely as the guiding principle for the foundation of mechanics and that part of physics which is based on it.

A demonstrative science in the Aristotelian sense—if his scattered remarks may be briefly summarized—is a system of enunciations on a given subject, satisfying the following requirements:

The terms used in the formulation of the statements are to be classified as undefined basic terms and definable derived terms. The statements themselves are either unproved fundamental propositions or demonstrable derived propositions.

With regard to the $\left\{\begin{array}{l}\text{undefined terms}\\ \text{unproved fundamental propositions}\end{array}\right\}$ it is required that they shall be $\left\{\begin{array}{l}\text{immediately intelligible}\\ \text{immediately evident}\end{array}\right\}$ and also sufficient for $\left\{\begin{array}{l}\text{the understanding}\\ \text{the demonstration}\end{array}\right\}$ of the derived $\left\{\begin{array}{l}\text{terms}\\ \text{propositions}\end{array}\right\}$ admitting of $\left\{\begin{array}{l}\text{definition}\\ \text{demonstration.}\end{array}\right.$

These two requirements may be designated successively as the intelligibility-postulate and the evidence-postulate. The fundamental propositions should, moreover, be necessary assertions, i.e. not only their validity, but also the necessity of their validity should be evident.

It is obvious that the idea of basing a branch of knowledge on axioms is inspired by mathematics. In Antiquity it was applied in the scientific sphere to the foundation of statics by Archimedes; and it will be met with again when we consider the growth of classical physics. So even Aristotle, who, unlike the Pythagoreans, the Atomists, and Plato, generally represents the a-mathematical element in the history of natural science, appears to have made a contribution to its mathematization nevertheless.

F. STOICISM[19]

50. Stoicism is a philosophical current with various ramifications, extending over several centuries (the so-called Old Stoa was founded about 300 B.C. by Zeno of Citium; the Middle Stoa, with which the names of Panaetius and Posidonius are associated, began about 150 B.C. and lasted until about A.D. 100, and this was followed until about A.D. 200 by Neo-Stoicism). This school was primarily interested not in natural philosophy, but in ethics. It is this fact which makes it impossible to add to the outline of Atomism and of the scientific sides of Platonism and Aristotelianism an equally detailed description of Stoicism. Only a few characteristic ideas about nature enunciated in the Old or the Middle Stoa, which in one

way or another have been of importance for the history of physics, will be mentioned here.

The Stoic doctrine of nature is based on the materialistic view that only material bodies can perform or suffer actions, and this only when they are in direct mutual contact. From which it follows that the human soul and its powers, and the qualities and properties of physical bodies, are likewise material. As they stand these statements give the impression that the world-outlook of the Stoics was closely related to that of the Atomists, and it seems strange that they should so fiercely hate and oppose the philosophical school of the Epicureans, which in its scientific aspect was continuing the work of Leucippus and Democritus.

But a fuller explanation modifies the first impression a good deal, so much so that one may sometimes think that a diametrically opposed view is being expounded, a dualistic instead of a materialistic-monistic one; it is as well to realize from the start that the latter characterization nevertheless remains valid.

51. The Stoa did in fact recognize as primary grounds of all things two original principles, which from their definition may be opposed dualistically as soul and body or as force and matter. One is an active principle, which on a large scale is called the World-Soul (*Λόγος*), expressed religiously as *Πρόνοια* (Providence), astrologically as *Εἱμαρμένη* (Destiny), and mythologically as Zeus, which acts as immanent efficiency and the rational law of nature, and which on a small scale permeates bodies as seminal reason (*λόγος σπερματικός*) and endows them with vitality and 'tonicity' (*τόνος*). The other is passive in character, it is pure matter devoid of qualities or *πρώτη ὕλη*, which is nothing definite as yet, but is susceptible of taking any form.

The distinction is also reminiscent of that between form and *prima materia* in Aristotle. The Stoic principles, however, may each exist *per se*, whereas those of Aristotle can only be distinguished in the substance by analytical thought. Above all, the one is just as material as the other; the Logos is merely a much subtler kind of matter than the *Ὕλη*, a warm, vivifying breath, an extremely fine current of gas (*πνεῦμα*), a fire endowed with creative power (*πῦρ τεχνικόν* or *νοερόν*), not to be confused with empirical fire (*πῦρ ἄτεχνον*), which consumes and destroys.

The active principle may permeate the passive principle, not in the manner of a mechanical mixture, in which the constituents continue to exist side by side, or a chemical combination, where one new substance is formed, but in the literal sense of an absolute penetration. During this permeation the primordial matter may take on one of the four first qualities, hot, cold, moist, and dry, thus passing into one of the four elements, each of which therefore consists of primordial matter *plus* one of the quality materials. If the quality taken on is dryness or moistness, the passive elements earth and water respectively are formed, which have only slight