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Aristotelian Physics

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1. Introduction

No other philosopher had such a deep and long-standing impact on Western science as Aristotle. In the fourth century BC he developed a fully comprehensive worldview that would with only few modifications stand for about two thousand years. Rather than just collecting isolated facts, he posed fundamental questions about nature and about the methods to study nature. Physics in the Aristotelian sense included the fundamental understanding of matter, change, causality, time, and space, which needed to be consistent with logic and experience. From that he derived a cosmology that allowed him to explain all phenomena, from everyday life to astronomy including both natural phenomena and technology.

Aristotle (384-322) lived in a time period of extreme political turbulences that deeply shaped his biography. When the 17-year old Macedonian moved to Athens to enroll at the famous Academy of Plato, the state of Athens had lost its former political hegemony, but still had an international reputation in education. Ten years later the King of Macedonia, Philip, began to conquer the Greek states, which resulted in growing anti-Macedonian sentiments in Athens. When his patron Plato died in 347 and Athens declared war against Macedonia, there was no way for Aristotle to stay longer in Athens. He escaped to Asia Minor before Philip employed him to tutor his aspiring son Alexander. This Alexander would soon conquer the by then largest empire, ranging from Greece eastwards to India and southwards to Egypt. Under the hegemony of Alexander the Great, Aristotle could peacefully return to Athens at the age of 49 to found a new school, called the Lyceum. Yet, when Alexander died only 13 years later and his huge empire immediately fell apart, it was again for Aristotle to hastily leave Athens, shortly after which he died.

One would perhaps not expect from somebody who lived on the move throughout his life that he developed a systematic, fully comprehensive worldview. However, Aristotle intellectual work was truly encyclopedic and covered fields as diverse as logic, epistemology, metaphysics, rhetoric, physics, chemistry, biology, psychology, political studies, ethics, and literature studies; and many of these disciplines, most notably logic and biology, can point to Aristotle as their founding figure. Even in mathematics, which Aristotle conspicuously neglected although it was then a major topic at Plato’s Academy, he essentially influenced Euclid’s (325-265) geometry through his axiomatic approach in logic. Moreover, Aristotle’s general approach to scientific topics became the standard scientific method for about two thousand years.

Whereas former philosophers mainly presented their views in an aphoristic or narrative style, Aristotle developed a systematic approach. For each issue he first collected all the views and arguments by his predecessors, which makes his work still a rich source for historical studies. Then he clarified the meaning of all the pertinent concepts and analyzed the various views if they could be reconciled or what their fundamental opposition was. To resolve a fundamental issue, Aristotle drew on different sources. Were the views in accordance with the available empirical data? Were the arguments sound? Did the views appeal to our common sense? Finally, did the views fit with the knowledge that he had previously established by the same method? Incrementally working through the entire realm of knowledge with this method, Aristotle built a stable philosophical system that covered almost any discipline. Since the pieces of knowledge were strongly related to each other, such that they could not easily be replaced, the system would stand for about two millennia with only little modification.

Timeline

384	Aristotle was born in Stagira, Macedonia. His father, Nicomachus, was a physician to the king of Macedonia; his mother, Phaestis, came from a wealthy family from the island of Euboea.
367	He moved to Athens to enroll in Plato's Academy, first as student and later as lecturer on various subject matters.
347	The war between Athens and Macedonia started and his patron Plato died. Aristotle fled to Assos on the coast of Asia Minor, where he married the daughter of his friend Hermeias, Pythias, with whom he had a daughter. He began his zoological studies.
345	Aristotle moved to the island of Lesbos and joined his former student Theophrastos in the study of biology.
343-340	The king of Macedonia, Philip, called Aristotle to his court in Mieza to tutor his son Alexander.
336	Alexander, the new king of Macedonia, began conquering a huge empire, eventually including all of Greece and ranging southwards to Egypt and eastwards to India.
335	Aristotle returned to Athens and founded a new school, the Lyceum, assembling scholars in all the fields of science and humanities. Most of his extant writings, many of which were lecture notes, are from this time.
323	Alexander died and his empire immediately fell apart. For a second time Aristotle fled from Athens, this time to Euboea in his home country.
322	Aristotle died at the age of 62.

2. The Causality of Nature

The English term 'physics' goes back to the Greek term '*physikē*' which means the knowledge and study of nature (*physis*, in Greek). Still in the early 19th century, physics meant about the same as natural philosophy and covered all the scientific disciplines. In antiquity, however, the fields of modern physics were either undeveloped (e.g. electricity, magnetism, and thermodynamics) or did not belong to physics. For instance, mechanics was but a craft like carpentry, and optics was a theory about visual sensation and, if geometrically describing the directions of rays, a part of mathematics. For Aristotle and his followers, mathematics was clearly distinct from physics, because it only described nature in geometrical or numerical terms. The task of physics was, however, to explain nature.

From a common sense perspective, Aristotle's approach is still appealing today because of his straightforward reasoning. For him, explaining nature meant answering why-questions about nature, such that scientists have fulfilled their duty only if all our why-questions are satisfactorily answered. He attentively observed that people asked four different why-questions that required four different answers; and since such answers were commonly considered to refer to causes, he accordingly distinguished between four different causes.

Hence, each of the four why-questions required a certain answer that referred to a certain cause. Let us consider an example question that covers the four different meanings: "Why does a knife cut meat?" If you respond that the knife is made of iron which is harder than meat, you are referring to the *material cause*. Arguing that the knife has a sharp blade provides the *form cause*. If you explain the mechanism by which the knife takes the meat apart, you give the *efficient cause*. And if you say that the knife can cut meat because that is the purpose for what it has been made, you provide the *final cause*. For a satisfying answer, you need to refer to all the four causes, although their relative importance may differ from case to case.

Of course, the meat-cutting knife is not an example of physics in the ancient meaning, because knifes are artifacts and not natural things. However, although natural things are different from artifacts, as we soon see, Aristotle was convinced that we ask the same four kinds of why-questions for natural things and artifacts. In particular, unlike modern physics, he thought that scientists must not forget the final cause in nature to provide satisfying answers. For instance, the blooming of a flower would not sufficiently be explained by a mechanism that details the events that make the blooming happening. A satisfying answer, according to Aristotle, needed to refer to the purpose of blooming, that it enabled the reproduction of the flower, which he thought was embedded in the flower like an unfolding program. Moreover, the flower has developed its proper form only in the state of blooming, and this proper form is not only part of our concept of flowers, it is also a constitutive part of the flower itself throughout its development.

Beyond the analogy of causes, Aristotle distinguished natural things from artifacts. Natural things develop and are what they are only by virtue of causes that are internal to them, in contrast to artifacts that are made by humans according to human goals, which are external to the objects. Examples of natural things are stars, animals, plants, stones, clouds, and basic materials; examples of artifacts are houses, furniture, cloths, and tools. However, the distinction is not a simple one. For instance, when a rotting knife loses its original form, it is still an artifact insofar as it is a knife, but it becomes a natural thing, a piece of matter, insofar as rotting is a natural process determined only by its basic material properties. Or, a hedge is natural insofar as it is a plant that grows owing to its own principles, but artificial insofar as humans have cut it to a certain form for human ends. Hence, the world cannot simply be divided up into natural and artificial things – it depends on how we conceive these things.

2. The Dynamics of Nature

Aristotle's physics is not about natural things in a static sense. Instead he was convinced that nature is essentially dynamic and that natural things are under continuous development. Thus, understanding a natural thing requires two aspects: we need to know, first, what the thing is composed of, and second how and why the thing alters. In response to the first question, Aristotle developed a metaphysical scheme that shaped his entire philosophy: every real thing, both natural and artificial, is composed of matter and form. For instance, a brick consists of clay in cuboid form. As long as the cuboid form is not materialized, as in geometry, it is not a real thing but simply a mathematical idea. On the other hand, real things can be the material of which other real things consist if they are arranged in a certain form. For instance, bricks are the material for building houses and, again, houses are the material of cities. We will soon see that Aristotle used this scheme to build up the entire cosmos.

To understand the dynamics of natural things, Aristotle distinguished between four kinds of processes. First a thing can just move in space without being changed. Second, a thing can grow or shrink, i.e. increase or decrease in size, without changing its characteristics. Third, a thing can undergo qualitative changes, without losing its identity, such when its color changes or when a tadpole transforms into a frog. Finally, a thing can emerge out of or turn into something entirely different, when, for instance, an animal dies and decomposes into basic materials or when basic materials chemically transform. Once we have identified the kind of change – whether spatial, quantitative, qualitative, or substantial – we can investigate the causes of change, which for Aristotle are both the efficient and final causes.

Aristotle's view of change includes further components that are necessary to understand his physics. In every change, something must persist throughout the process. While this is obvious with spatial and quantitative changes, it is more difficult to identify what persists in qualitative and, particularly, substantial changes. According to Aristotle, the matter of each real thing persists while only its form changes. For instance, when we form a mug from a lump of clay, the clay persists and gradually changes only its form from that of a lump to that of a mug. Since we cannot shape any form out of clay, for instance no spider web, matter and form are related to each other in a certain way. Thus, clay has the potential to assume the form of a mug, but not that of, say, a spider web. This is more important for natural processes, where the causes of changes are internal to the natural things that change. For instance, the matter of a tadpole has the hidden potential to assume the form of a frog instead of a bird or something else. Therefore, Aristotle also described any process as a change from potentiality (a potential frog) to reality (a real frog).

Furthermore, Aristotle thought that any change requires some interaction between the changing thing and the cause of change, and that the change immediately ends when the interaction stops. (We will later see that this idea was revised in early modern mechanics.) For instance, if we heat some water with fire, fire acts on water because water, unlike for instance light, is susceptible to the action of fire; and as soon as we stop heating, the water cools down. Similarly, if a change is driven by a final cause, the object of change needs to be susceptible to this final cause and stops changing as soon as the final cause is removed.

4. The Elements of Nature before Aristotle

One of Aristotle's most persistent contributions to science, and indeed the core of his physics, was his theory of the elements. That theory was ultimately overcome only by the end of the 18th century in the so-called Chemical Revolution. Apart from astronomy the theory of the elements was the core issue of any ancient philosophy of nature. It was expected to explain the plurality and change of all matter, i.e. what we today call chemistry and particle physics. However, unlike today's experimental sciences, ancient philosophers rarely referred to experiments but, instead, searched for consistent and comprehensive rational systems that were in accordance with all available empirical data from the observation of nature. Before we deal with Aristotle's solution, we briefly look at those of his predecessors.

For most of the early ancient, pre-Socratic philosophers of nature, we have only indirect reports and few extant fragments that remain difficult to understand. It seems that since the 7th century BC, Greek philosophers proposed various solutions that all broke with their religious traditions. Instead of referring to gods, they characterized the ultimate principles of nature by material properties. Many of the early pre-Socratics were monists, arguing that a single material principle underlay the plurality and change of all matter. For Thales (ca 624–546 BC) this principle was water, whereas Anaximenes (ca 585–525 BC) considered it like air and Heraklitus (ca 535–475 BC) rather like fire. Pluralists, like Anaxagoras (ca 500–428 BC), assumed that the infinite plurality of things required infinite many different principles, so that any change is owing to the mixing and separation of the elements. Based on the idea of Pythagoras (ca. 580–500 BC) according to which everything is founded in the dualism of opposing principles, Empedocles (ca. 490–430 BC) developed the first ancient synopsis on which Aristotle would draw. He combined the earlier suggestions of water, air, and fire with earth into a system of four elements that could interact with each other by the opposing principles of attraction and repulsion to form the plurality of all things.

In retrospect, the most interesting account is perhaps the atomism by Democritus (ca. 460–370 BC) which went back to earlier ideas by Leukippus (5th century BC). On the one hand, Democritus' atomism resembled the pluralism of Anaxagoras, because Democritus claimed that there were an endless number of different kinds of atoms that form the variety of things and that any change is owing to the separation and mixing of atoms. On the other, ancient atomism was a dualistic doctrine, because its proper principles were matter and void. Thus, atoms (from Greek *atomos*, indivisible) were conceived as a certain distribution of matter and void, such that matter forms invisibly small regions of irregular shapes that persist through all changes in time.

Atomism was a prominent but much contested doctrine throughout history. Its critics, first among them Aristotle, had many severe objections. A prominent metaphysical argument pointed to its inconsistency. Since matter, according to Democritus and unlike all the other philosophies of nature, had no material properties, it was unclear how matter differed from void. When Democritus argued that matter was 'full' whereas void was empty, critics objected that the empty void was not a principle of nature but merely nothing, and that claiming the existence of nothing was a plain contradiction. That debate continued up to early modern times as the question of whether or not the vacuum exists. Another critique referred to the highly speculative manner of atomism, since there was no empirical evidence for the existence of atoms. Moreover, since matter had no material properties, every explanation of material properties by reference to the shape of atoms was highly speculative. Indeed, Democritus and his followers arbitrarily claimed various shapes to explain differences in color, taste, or any other empirical properties. Furthermore, atomism was an extreme stretch for common sense reasoning. The ideas that matter would at a certain point be no more divisible into smaller parts and that matter has no intrinsic qualitative properties were counter-intuitive, because empirical evidence suggested just the opposite.

Aristotle's teacher Plato (427–347) developed his own version of atomism that drew on earlier ideas from the school of Pythagoras, some sophisticated mathematics, and the doctrine of Empedocles. Although it was esoteric even for contemporaries, it became influential because Plato described his theory in the form of a divine creation myth that was reconcilable with the biblical creation myth. This made a digest of his text the only piece of ancient Greek natural philosophy known to medieval Christians up to the 12th century. In it, the divine but artisan-like creator builds the world according to geometrical ideas by shaping not matter but space. Thus, Empedocles' elements of fire, air, water, and earth consisted of four invisibly small regular polyhedra. However, the polyhedra were not atoms but consisted of indivisible triangles of two different types. Plato selected their mathematical construction in such a way that several material changes, e.g. fire boils water to become air-like steam, could be explained by a quasi-geometrical mechanism. For instance, the sharp-edged tedrahedra of fire could split the blunt-edged dodecahedra of water into their composing triangles which then could reassemble to form the octahedra of air.

5. Aristotle's Elements of Nature

Aristotle rejected both kinds of atomism based on the arguments presented above. In addition he argued that Plato's atomism confused mathematical ideas with real things. Instead, he preferred Empedocles' four elements to which he provided a new foundation. In Aristotle's view, the elements of nature must represent the fundamental characteristics of nature, i.e. they must bear the basic properties of matter that drove the dynamics of nature. From an empirical point of view, the basic characteristic of matter was its tangibility, which for Aristotle included two tactile property dimensions: matter is more or less dry (hard) or wet (soft) and more or less cold and hot. To cover the whole realm of these two property dimensions, each element must bear one extreme property from each dimension, which resulted in four pairs of properties to which Aristotle related Empedocles' four elements: dry and cold were the characteristics of earth, wet and cold those of water, wet and hot those of air, and dry and hot those of fire (see Figure 1). Moreover, for Aristotle hard and soft were passive properties, because they determined the malleability of materials, whereas hot and cold were active properties in that they could act on other materials. For instance, water expands if it is heated by fire and shrinks if it is cooled. The two pairs of properties thus represented both the empirical characteristics of matter and the basic interactions between materials.

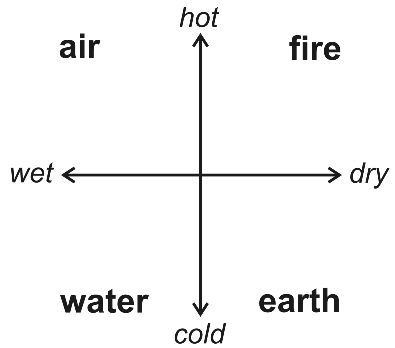

Figure 1: Aristotle derived his four elements of matter from the two pairs of opposing qualities dry/wet (hard/soft) and cold/hot.

Aristotle used his theory of the elements to explain a wealth of natural phenomena ranging from chemistry, physics, and meteorology to biology and medicine. Moreover, his theory allowed him to write the first treatise on what we would nowadays call the chemical processing of materials, including metallurgy and cooking. On the level of basic materials, there was no fundamental distinction between natural and technological phenomena, because the materials and their interactions were essentially the same in natural and artificial processes. Furthermore, the elements served him to structure the entire world in two different approaches, to which we turn now.

6. The Hierarchical Structure of the World

Like in Plato's theory, Aristotle's elements could interact with each other resulting in elemental transformation. When an excess of fire (hot & dry) acted on water (cold & wet) to neutralize the elemental property cold, water turned into a kind of air (hot & wet). For Aristotle, the elements were real things, although they naturally occurred only in impure form or mixtures. According to his metaphysical doctrine, the elements must themselves be composed of form and matter as any real things (see above), and he decided that their elemental properties were their specific form. In elemental transformation, which was his paradigm case for substantial change, the elemental form was replaced. His general theory of substantial change required that a primary matter, bare of any qualities, persisted through the change. Since the primary matter had no qualities and no form, it was not a real thing for Aristotle but only the bearer of elemental properties and the substratum of substantial change that united the physical world. Nonetheless Aristotle's primary matter would later inspire numerous misunderstandings, particularly among alchemist in their experimental search for the basic principle of matter.

Starting with the elements composed of primary matter and their specific form of elemental properties, Aristotle developed a hierarchy of the physical world in which each step provided the matter for the next step. For basic compounds, the elements served as matter and their composition as specific form. In the next step of heterogeneous compounds such as wood, the basic compounds were spatially structured according to a specific form. Heterogeneous compounds could be combined and structured to form parts of living beings, like a human arm or the trunk of a tree. If such organs were combined and organized according to certain forms and ends, they would form a living being, for which Aristotle required at least a vegetative soul as their organizing principle and for the control of their metabolism. Animals differed from plants by an additional higher order soul that allowed living beings to perform locomotion and sensation. Finally, humans were additionally endowed with an intellectual soul that enabled them to organize their life according to ideas and goals. Also the inorganic world, including air, water, and earth, was spatially and chronologically structured to form regular and periodical phenomena like the weather and the seasons, for which Aristotle identified the sun, the moon and the stars as their structuring and moving principle. Finally, since for Aristotle every movement must have a cause, he postulated gods as the ultimate cause of the regular motion of the stars. Like primary matter, these gods were no real things composed of matter and form. Rather, like the human intellect that can organize real events through its non-material existence and activity, these gods were pure form and so-called ‘unmoved movers’. Entities of complete independence and modesty, these gods also served as models for human beings.

7. The Cosmological Structure of the World

His theory of the elements helped Aristotle to structure the entire world also spatially. Indeed he designed the cosmos in spherical shells, each related to one element, around the earth sphere. It was well known in ancient Greece, even measured with some precision, that the earth forms as sphere of a certain size. The earth obviously consisted mainly of the element earth, its surface was largely covered with water, and the atmosphere was dominated by air. Only the lower atmosphere was filled with moisture, clouds and rain, owing to atmospheric turbulences at the interface between the shells of water and air, which determined the weather. Above the atmosphere, the next sphere reaching up to the height of the moon, was filled mainly with the element fire. Aristotle could refer to ample empirical evidence of his elemental shell model. In particular, earth was heavier than water, which in turn was much heavier than air; and fire flames obviously moved up in the air. In water, a stone sank down whereas a bubble of air rose up. Based on such empirical regularities he drew the general conclusion that each element tended to move to its specific shell which he called its proper place. This thesis could also explain any ordinary phenomenon on earth that we nowadays, following Newton, explain by the force of gravitation.

Above the moon, things were obviously different since the sun and the stars, including the planets, appeared to move in semi-regular circles around the earth, a motion that was, without the help of extra-forces, unfamiliar on earth. Because of the obvious departure, Aristotle postulated that the stars and their surroundings were composed of an entirely different matter unknown to humans, which he called ether and which should enable circular rather than straight motion. In his explicit astronomy, Aristotle drew on his contemporary astronomer Eudoxos (c. 408-355). Faced with the semi-regular orbits of the stars, Eudoxos had developed a complex geometrical model that explained the irregularities by the superposition of many regular circles. This geocentric cosmological model, with the earth at the center around which all the celestial bodies moved in circular orbits, was later developed in greater detail by the Greek mathematician and astronomer Ptolemy in the second century AD. However, as early as the third century BC, an astronomer from Aristotle’s own school, Aristarchos of Samos, suggested that the sun would be in the center of the cosmos with the earth moving around the sun. This heliocentric model, although known to many succeeding astronomers, could not gain acceptance before Copernicus in the 16th century developed it with mathematical rigor such that it could explain the irregular orbits with greater precision than its rival models.

Aristotle’s cosmology would be incomplete without his views on space and time. If you ask, what is in the space beyond the sphere of the stars, Aristotle would have responded that this question has no meaning because there is no space beyond the sphere of the stars. For him the entire cosmos was a huge but finite sphere composed of matter, such that each element, including the ether, had its specific place. Space without matter did not exist, indeed was a misleading concept for Aristotle both in cosmology and in atomism. Unlike the finite space, he conceived time as infinite, without beginning and end. The cosmos existed since eternity and will exist for all eternity, because both its emergence out of nothing and its vanishing into nothing violated the basic principles of his metaphysics of change. Moreover, owing to the regular movement of the stars, and ultimately to the eternal nature of the gods, there were neither radical nor evolutionary changes on earth. Indeed, Aristotle believed that biological species did not evolve but instead were stable kinds like, for instance, minerals. Even if, by some natural disaster, some species disappeared, the long-term balanced conditions on earth would enable their reemergence.

8. The Medieval Reception of Aristotle's Natural Philosophy

The impact of Aristotle's philosophy can hardly be overestimated. First the Islamic culture from the 8th century onwards and then the Christian culture from the 12th century onwards grew from purely religious cultures to intellectual cultures largely through the translation of and commentaries on Aristotle's writings. Through these efforts both Arabic and Latin not only developed to intellectual standard languages but also incorporated Aristotle's vocabulary, concepts, and philosophical views. The impact was so deep that the development of most of modern science from the 17th through the 19th century was a decided effort to overcome the Aristotelian system.

The earliest translations of Aristotle's scientific works from Arabic to Latin in the 12th century at first caused a deep shock among Medieval Christians. Up to then they had known Aristotle only through fragments of his logic, which had made him the unquestionably authority in all logical and philosophical matters. Now they learned that the revered philosopher had taught that the world was not created by God, as the Bible said, but eternal without beginning and end. Moreover, Aristotle had confined gods to be 'unmoved movers' who guaranteed the eternal movements of the stars, without being able to intervene in the cause of events, to say nothing about the creation of biblical miracles or the role of angels. In addition, as one of the greatest Arabic Aristotle scholar, Averroes (1126-1198), had shown, the human soul could not, according to Aristotle, individually survive physical death, which undermined the Christian doctrine of the soul's immortality. Thus, the first reaction by Christian authorities was to ban the teaching of Aristotle's science altogether on death penalty. However, Albert the Great (c. 1200-1280) and particularly his pupil Thomas Aquinas (c. 1225-1274) undertook enormous efforts to reconcile Aristotle's natural philosophy with the Christian doctrine by writing voluminous commentaries that explained in great detail how Christians should interpret Aristotle's texts. Thanks to these commentaries, Aristotle's revised natural philosophy moved into the core curricula of the newly established European universities where it remained a central part for at least four centuries. Furthermore, Aquinas' blend of Aristotelian and Christian views, which came to be known as Thomism, was made the official doctrine of natural philosophy and metaphysics by the Catholic Church, and has remained so up to today.

The theological assimilation brought Aristotle's natural philosophy an extraordinary status. On the one hand, any criticism or different views were threatened by official sanctions, ranging from the ban of teaching and publishing, to excommunication and death penalty, as it was executed, for instance, on Giordano Bruno (1548-1600). On the other, it closely related natural philosophy to theology, such that debates on natural philosophy, including attempts to overcome the Aristotelian system and to establish what we nowadays call modern science, were deeply religiously motivated. Furthermore, since Aristotelian natural philosophy was administered by the Catholic establishment, criticism grew particularly along with the Reformation movement against that establishment.

9. Early Modern Approaches to Overthrow the Aristotelian System

Apart from the Christian assimilation, Aristotle's natural philosophy was a strong system based on metaphysical principles that were difficult to change incrementally. Therefore, changes had to be radical to build a new system on different fundamentals. On the other hand, any such radical change was threatened by Church persecution and would not find many followers. The French philosopher and mathematician René Descartes (1596-1650) solved this paradoxical task by building a new system based on selected and remodeled Aristotelian principles. Whereas Aristotle had claimed four different causes in nature (formal, material, efficient, and final) which scientist must seek to explain natural phenomena, Descartes selected only the efficient cause. The task of scientists, according to Descartes, was to explain all natural phenomena solely by its causal mechanism. Similarly, of Aristotle's four kinds of change (spatial, quantitative, qualitative and substantial), Descartes choose only spatial motion and declared that any qualitative or substantial change could ultimately be reduced to the motion and collision of particles in space. He remodeled Aristotle's principles of form and matter to become geometrical form and spatial extension and characterized the elements by the geometrical form and size of particles rather than by the elemental qualities of hot, cold, wet, and dry. In the end, Descartes' universe strongly resembled ancient atomism with invisible particles swirling around, but he rejected both the ideas of an empty space or vacuum and of indivisible particles.

Descartes' new emphasis, however, was the programmatic idea that the mechanism of any motion of particles, and thus the explanation of any natural phenomena, should be treatable by mathematics. To that end, he formulated a set of mathematical principles that would strongly influence Newton's later mathematical principles of mechanics. Indeed, Descartes (as well as simultaneously Galileo) formulated, what we now know call the principle of inertia, according to which a body once moved by an external cause tends to continue its motion in straight direction as long as no other external cause interferes. This principle was an important departure from Aristotelian physics in two regards. First, whereas Aristotle had taught that any motion or change continues only as long as the moving cause is effective, the principle of inertia required only a moving cause at the very beginning of the movement. With respect to the entire universe, an initial impetus would suffice to cause all the succeeding dynamics of the universe. That idea was theologically appealing to Descartes and his followers of mechanical philosophy because it allowed remodeling Aristotle's 'unmoved mover' into a Christian Creator God who had once started the dynamics of the universe by one initial impetus. Second, since Descartes (unlike Galileo) claimed his principles to be valid for all motions, both on earth and in the celestial sphere, he rejected the Aristotelian distinction between earthly and celestial physics. In particular, he dismissed the prominent idea that the natural motion of the stars would be circular rather than straight as on earth and, instead, tried to explain the quasi-circular movement of celestial bodies by gigantic vortices of celestial particles. This approach, including its insufficiencies, would later inspire Newton to unite earthly and celestial mechanics based on the common force of gravitation.

Descartes' emphasis of mathematics was combined with a rationalist methodology that in scientific matters trusted more in rational arguments than in empirical evidence. However, since the 16th century, another branch of mathematics flourished that, after the model of the ancient mathematician and engineer Archimedes (c. 287-212 BC), employed empirical measurements for the solution of engineering problems. The boost of military engineering brought the motion of projectiles to the fore, which would ultimately become a central element of mechanics as the core discipline of modern physics. In an effort to maximize the range of projectiles, the Italian military engineer Nicolò Tartaglia (1500-57) meticulously described the trajectories of projectiles depending on various parameters. He was the first to analyze the curved trajectory as being simultaneously caused by the (artificial) impetus in the direction of the shot and the (natural) gravity straight down to the earth. Once analytically separated, the two components of the motion could become subject to further empirical studies. Thus, the Dutch engineer Simon Stevin (1548-1620) let two lead projectiles of different size fall down by gravity from the same height and concluded that their velocity was the same regardless of their weight. That contradicted the physics of Aristotle, who had come to the opposite conclusion from the different velocities of, say, a metal piece and a feather. The Italian mathematics professor Galileo Galilei (1564-1642), to whom Stevin's experiment has wrongly been attributed, further studied the motion of falling bodies by combining metaphysically inspired mathematical hypothesis with measurements. He reasoned that all natural motions must be mathematically simple and assumed that the simplest motion, that with constant velocity or the distance being proportional to time, was reserved for celestial bodies. Therefore, he postulated that freely falling bodies on earth moved according to the second simplest motion, i.e. with constant acceleration or velocity being proportional to time. Because clocks at that time were much too inaccurate to prove his hypothesis with falling bodies, he modified the experiment and measured the time that a ball needed to roll down an inclined plain. The measurements confirmed his mathematical hypothesis which came to be known as the law of free fall. It allowed Galileo to describe Tartaglia's trajectories as parabolic curves and to prove mathematically what Tartaglia had shown only by empirical tests: the maximum range of projectiles was achieved when the shot was made at an angle of 45°. It was up to Newton, however, to integrate this law of motion into his general mechanics that combined celestial and ballistic motion in a uniform mathematical theory centered on the force of gravitation.

Mechanics was but a marginal part of Aristotle's comprehensive natural philosophy, because outside of astronomy it was rarely about natural phenomena. Although the rise of mathematically based mechanics by Descartes, Galileo, Boyle, Newton and others has later been called the Scientific Revolution, it did not touch on most scientific topics covered by Aristotle. Indeed these topics, which further formed the major part of the scientific disciplines, continued to be deeply influenced by Aristotle's philosophy for centuries. Particularly his principles of biology would stand almost unmodified well into the 19th century, before evolutionary ideas became prominent, culminating in Darwin's theory of natural selection. Furthermore, since the mechanical explanation of chemical phenomena by reference to the motion of speculative particles turned out to be rather fruitless, Aristotle's theory of elements and compounds would still in the 18th century serve as the basis in chemistry, mineralogy, meteorology, geology, and medicine.

In retrospect, this theory of the elements of matter was suitable to cover what we today call thermodynamic phenomena, e.g. the boiling or freezing of water, rather than truly chemical transformations. Since it claimed even the possibility of elemental transformation, it inspired experimental attempts at transforming matter at will in laboratories equipped with increasingly complicated apparatuses. In essence, Aristotle's doctrine of the elements became the theoretical foundation of medieval alchemy which, in its laborious efforts, developed towards the very non-Aristotelian approach of understanding nature by transforming it. Eventually that would become the approach of modern experimental laboratory science. Despite their little success in goals such as gold-making, alchemists or 'chymists', as they were called since the 16th century, literally created a plethora of new materials and chemical phenomena in their laboratories that called for other theoretical approaches than the Aristotelian one. For many centuries the Aristotelian elements were only supplemented by additional 'chymical principles' to account for such chemical phenomena as burning, calcination, or acid-building. It was not before late 18th century, however, that the theory of matter was put on a new, experimental basis. Instead of conceiving the elements in a metaphysical system, as Aristotle had done, Antoine Lavoisier (1743-1794) and his followers considered any material a true element of matter which resisted any experimental effort at taking it apart. The science of matter had to start anew, first in experimentally searching, identifying, and characterizing the elements and then in developing theoretical concepts that explained the properties of materials from their elemental composition.

Even though most of Aristotle's scientific answers are now outdated by modern science, his texts are still worth reading. He posed the kind of questions that still drives current science and that inspires young people to study science. Moreover, since his scientific answers are deeply grounded in common sense, understanding Aristotle's science helps today's science teachers appreciate the gap that ordinary people need to bridge in order to understand modern science.

Further Reading

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