FROM QUINTESSENCE TO QUARKS

Physics

A Short History

J. L. HEILBRON

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INTRODUCTION: THE GREEK WAY

The Superconducting Super Collider (SSC), the dream of American high-energy physicists, would have had a circumference of 87 kilometers and a price tag of billions of dollars. Its proponents justified the expenditure on several grounds. On the high ground, it would probe the universe to philosophical depths and thus "keep faith with the Greeks." Below ground, it would advance tunneling technique and give society perfect sewers. Congress cancelled it in 1993.

The undertaking represented by the SSC might be the way to an ultimate physics. But it is not the Greek way. In antiquity, physics was philosophy, a liberal art, the pursuit of a free man wealthy enough to do what he wished. He did not aim to improve sewers and, since he had no need of public money, did not have to claim that he would. Nor did he want apparatus, since he seldom experimented, or mathematics, since he seldom calculated. The few ancient applications of mathematics to physics constituted a mixed science devoted to the description of phenomena rather than to the search for principles.

In the tripartite division of Greek philosophy, physics stood between logic and ethics. It inquired into the principles regulating the physical world from the high heavens to the Earth's center, and from the human soul to the life of the least of living creatures. It thus functioned as a natural theology—defining man's place in nature—and as a necessary approach to ethics, or the principles of a good life. For two millennia the main practical value of physics lay in the ethical consequences of its versions of the way the world began and persists.

Greek physics, with its eye to ethics, its indifference to mathematics and experiment, and its independence of states and courts, is sufficiently distinct from an enterprise conducted by salaried teams requiring elaborate technologies and mathematical analyses to deserve a different name. Let it be *physica* and those who cultivated it *physici*. This short book describes some of the ways by which ancient *physica* became modern physics. It does not ransack history to find items in ancient and medieval science that look like physics, but sketches the place and purpose of *physica* in the societies that supported it. Hence the primary site(s) of cultivation receive special emphasis: the independent private school (antiquity), court and library (Islam), university (later Middle Ages), court again (Renaissance), academy (late seventeenth and eighteenth centuries), university again (modernity), and university-government-industry (postmodernity). Of course, successive forms did not annihilate their predecessors. Academies of science survive, primarily as honorific societies and depositories of history, although a few flourish as national channels for funding, consultation, and outreach. The scientific advisory apparatus of government may be considered the descendant of courtly science; and the Greek schools, with their characteristic discursive style, continue in the myriad seminars in which the world's nascent science is presented and anatomized.

The story of the SSC may do service as a double symbol: through its cost, size, and design, of the transformation of *physica* into physics; through its cancellation, of the ongoing dilution of the dominance of the United States within an increasingly competitive international system.

Fig. 1. Schools of Athens. Raphael's evocation of the intellectual vigor, diversity, and discursiveness of Greek science.

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INVENTION IN ANTIQUITY

Tradition follows Aristotle in identifying the earliest *physici* as some gentlemen of Miletus, a flourishing Greek city on the coast of Anatolia, and in specifying half a dozen other Greek speakers as their successors. In this philo-Hellenic creation myth, no Greek *physicus* learned anything of any importance from a barbarian during the 250 years between the times of the eldest Milesian, Thales, and Aristotle. The story that Pythagoras, if he existed, did so partly in Egypt, suggests outside input; and studies of cuneiform texts reveal a natural knowledge among the Babylonians in some ways more advanced than that of the ancient Greeks. Still, the essential criterion that Aristotle used to identify his predecessors was not that they were Greek, but that they had conquered a paralyzing prejudice. Despite robust contrary evidence, they believed that the natural world runs on law-like principles discoverable by the human mind and immune from interruption or cancellation by meddling gods and demons.

Whether or not the Milesians deserve the blame or credit for this bold departure, it underlies and circumscribes all forms of *physica*, natural philosophy, and physics. Its implications go farther even than replacing caprice by law-like behavior. Since the gods displayed all too faithfully the traits and behavior of human beings, de-deifying implied (to speak Greek) deanthropomorphizing. The progress of physics has continued to remove human quirks and qualities projected on to nature. Thus nature, or the objective world, came to lose not only benevolence, malevolence, and color, but also such apparently indispensable attributes as space, time, and causality.

Of the four main schools of ancient philosophy, Aristotle's paid greatest attention to *physica* (see Figure 1). Having a particular interest in zoology, he derived his fundamental principles with an eye to the classification of animals. Because of his emphasis on *physica* and because his philosophy dominated during the Middle Ages and beyond, convenience advises taking it as normative. In antiquity, however, it had to compete with Platonic, Epicurean, and Stoic philosophies. The fluctuating market share of a school reflected the reputation of its leader as well as fad and fortune. Typically, its premises, library, and other assets passed from the founder to his senior disciples, and, perhaps consequently, the schools bore names suggestive more of real estate than of scholarship: the Academy (Grove) for the Platonists, Lyceum (a shrine) and Parapatos (a place for walking) for the Aristotelians, the Stoa (Porch) for the Stoics, and the Garden of Epicurus.

During the 800 years from the founding of the Academy in Athens and its refounding in Alexandria, the four schools underwent many reversals of fortune, including dissolutions and amalgamations. When operating, they were forums for free discussion of the sort practiced in political circles, but centered on studies pursued for personal improvement rather than for civic or financial advancement. Although they had members who studied with them for decades, they also admitted students who sampled each in turn. When Romans like Cicero frequented the schools of Athens they took advantage of this *Lernfreiheit*. The Pythagoreans did not form such a school, as they did not tolerate deviations from their doctrines and way of life, and acted ruthlessly against members who revealed their secrets.

Physica

Although *physica* ran from astronomy through zoology to psychology, limitation of coverage to cosmology and cosmogony, as in this book, is not unacceptably anachronistic provided we recognize that the same principles of structure and change applied to all natural processes. This truncated *physica* corresponds to the books of Aristotle dealing with general principles (*Physica*), the heavens (*De caelo*), the region between the Moon and the Earth (*Meteorologica*), and the creation and destruction of things on or in the Earth (*De generatione et corruptione*). These books (and the rest of the corpus from logic to ethics) became available in a standard format edited around 60 BCE from the lecture notes Aristotle bequeathed to his successors. They constitute the main parts of a theory of everything, or, as the moderns say, a TOE.

Cosmologies

The first TOEs Aristotle stepped on belonged to the Milesian monists. He then took on more generous materialists: Leucippus and Democritus, who allowed two principles, atoms and the void; Empedocles, who accepted the three Milesian elements (water, air, fire) and added earth to complete the tetrad; and Anaxagoras, who admitted an infinite number of different sorts of stuff. There were also those whose matter had no stuff at all, Pythagoras notably, for whom number had an independent existence—a concept that made no sense to Aristotle. The Pythagoreans' deduction that there must be a counter earth circulating opposite ours around a central fire (to raise the number of heavenly bodies to the holy tetractys) proved to Aristotle both the falsity of their *physica* and the nonsense to which numbers can lead.

Aristotle's teacher, Plato, had some sympathy for Pythagorean numerology and a belief in the importance of mathematical patterns for cosmological architecture. He took as his material not only mathematical abstractions but also supersensible idealizations of classes of objects: for example, the Idea "Horse," in which individual horses "participate" more or less, but always imperfectly. Consequently, although Plato was optimistic about the possibility of knowing the ideal world and even the supreme Good that made the Ideas and their relations intelligible, he did not allow the possibility of true knowledge of the things of this world. Since no material individual could express an Idea perfectly, our *physica* can never be other than fuzzy.

Physica comes from "physis" meaning "nature," which, according to Aristotle, "is the source or cause of being moved or being at rest." What makes things move? The early *physici* adumbrated four causes of change that Aristotle later codified. The monists and the atomists considered only the material cause. Empedocles and Anaxagoras provided action by taking some principles to be active and others passive—vague glimpses of efficient causes. Others saw the need to explain order in a universe of change and hinted at a teleological or final cause, such as set by a cosmic Mind. And Plato supplied a fourth cause, the formal, the Idea in which a thing participates.

Aristotle's inventory of the cosmological ideas of his predecessors, including anticipations of the four causes of change, was not an idle retrospective. It confirmed, and even proved, that he had not overlooked anything fundamental. "Of all who have discussed principles and causes none has spoken of any kind except those which have been distinguished in [my] discourses on Physics. They are all unmistakably, though obscurely, trying to formulate these." Aristotle's TOE, thus established as complete, makes use of some special concepts. A *substance* is any individual thing. The collection of its properties constitutes its *form,* which, contrary to a Platonic Idea, occurs only in union with *matter.* Form can be divided, although only mentally, into *essence,* which makes a substance the sort of thing it is, and *accidents,* which can change without causing the substance to alter its essence or kind. The essences of the four elements are easily stated: fire is dry, hot, and absolutely light; air is hot, moist, and relatively light; water is cold, moist, and relatively heavy; earth is cold, dry, and absolutely heavy. The elements can transform into one another, as fire evaporates water into air. An essence is usually compatible with a wide range of accidents: Socrates may be warm or cold, but heated or cooled too much he will cease to be Socrates.

It may now be intelligible to state that a substance's matter and essence are its material and formal causes, and that the active qualities hotness and moistness are the principal efficient causes of change. The final cause is the purpose for the existence of a form. Heavy bodies have gravity so as to fall toward the center of the world, and light bodies have levity so as to be able to rise toward the heavens, to restore order disrupted by the activity of animate creatures or the revolutions of the celestial spheres. These spheres and the stars and planets they carry cannot be made of the four elements, whose forms require that they move when unimpeded in a straight line toward or away from the world's center. There must therefore be a fifth element, a *quintessence*, which, obeying its formal and final causes, circulates around the universal center. With these few principles and some ad hoc adjustments, Aristotle worked his way from the Mind of the Unmoved Mover, which, as it can think only of the most sublime thing, can think only of itself, down to the mind of man, which, though no less selfish than the Mind of the Universe, is subject to frequent change like everything else below the quintessential heavens. And where there is change, there cannot be certainty; the best a *physicus* can do is to find a "rule [that] applies to what is always true or true for the most part."

A few deductions from Aristotle's approximate *physica* that came under sustained scrutiny will give some impression of its general character. Every motion, whether change of place or color or species, requires an external mover. Since none is available in a vacuum, where there literally is no place (no reference material) by which a body could orient itself, there can be no vacuum. Hence the flight of an arrow implies a vortex in the air, which cedes a place to the tip while slipping in behind to provide a push at the tail. The ambiguous role of the air, offering both resistance and propulsion, made an obvious difficulty. Another awkwardness arose from the absolute dichotomy between terrestrial and celestial physics. Because the heavens cannot change, transient phenomena that appear to take place there, like comets and meteors, must have their seat with lightning and the weather in sublunar regions.

Nothing, however, is more obvious than that the Sun influences the weather. How? Sometimes Aristotle wrote as if he thought that the Sun was hot, which would violate his proscription against terrestrial qualities in heaven. More often, he ascribed the seasonal powers of the Sun to its annual revolution, which, together with the rolling of the quintessential spheres, continually stirs up the sublunary regions. These disturbances cause moist and dry vapors to rise from the earth. Precipitation results from the moist exhalation, winds from the dry. "The same stuff is wind on the earth, and earthquakes under it, and in the clouds thunder." Lightning and thunder are dry exhalations breaking free from the clouds like pips squeezed from a fruit. The rainbow is a reflection from the clouds. Aristotle described it, in a manner unusual for him, geometrically: the Sun, the eye of the observer, and the center of the bow lie on a straight line that cannot exceed a certain angle with the horizon. This factoid would have a long and influential history.

Despite the continuing operation of final causes, the world is not in perfect order. The frictional drag of the turning lunar sphere on the stationary region of fire below it produces such anomalies as fiery meteors in the air, mountains above sea level, and water below earth. In the big picture, however, the universe resembles an onion. Peeled from the outside in, it discloses the fixed stars, the planets and luminaries in the conventional order Saturn, Jupiter, Mars, Sun, and Moon, and, in slight disorder, the elements Fire, Air, Water, and Earth. What is outside the skin? Here the onion analogy fails. There is literally nothing there. And just as there is no space not included in the visible universe, there was no time at which it did not exist.

Cosmogonies

Aristotle's world picture thus lacked a creator. So did the atomic theory of Democritus, who, nevertheless, offered a creation story for the visible universe. It began to be when a clutch of the infinity of atoms bouncing about in the infinite void happened to come together in a great vortex from which the largest fell to the center, forming the Earth. From what remained, centrifugation produced the air, the luminaries, the planets, and the stars. Although all things are made of the same dull stuff, they appear different to us because our sensory systems can build rich images from the few properties (size, shape, motion) of their constituent atoms. Epicurus added a spontaneous "swerve" to explain how atoms, falling in parallel through the void, occasionally collide and concatenate a world. According to him, the soul can exploit the swerve to choose to live the good life in an otherwise pointless universe. Since the Epicurean did not have to fear gods in this life or anything in the next, he could take moderate enjoyment of the flesh and free employment of the mind as the greatest goods. The inevitable erosion of all sound doctrine has transformed Epicurus' sober happiness into selfish hedonism, and his name into an eponym for refined pleasure.

Whereas the atomists allowed for the creation of many worlds in space and time by random accretion of their parts, the Stoics supposed that the single cosmos they admitted, geocentric like Aristotle's, is alternately destroyed and recreated. In place of disparate atoms, the Stoics put a continuous prime matter; and in place of bumps and grinds, "pneuma," a self-moving elastic compound of fire and air that gives matter its cohesive and other properties. Strict causality applies everywhere, guaranteed and effected by the spatial continuity of the pneuma, whose changing tension drives the world through repeated identical thermodynamic cycles. The system would seem to rule out free will decisively. But since ethics required a free acceptance of fate and the mental preparation necessary to meet it, Stoics had to find a way around the strict causality of their physics. Their solution was no more plausible than the Epicurean swerve. As an alterative to strict atomism, however, the Stoic concept of a space-filling active elastic spirit had a future.

In contrast to the Peripatetics with their unchanging uncreated cosmos, and the atomists and Stoics with their random and cyclical worlds, the Academics had a full cosmogony, with a creator as well as a creation story. As told by Plato's mouthpiece, the mathematician Timaeus of Locris, the Demiurge who made the realm of Ideas and the World Soul used what he had left after rolling out the celestial equator and the paths of the planets to manufacture a swarm of human souls. These he sent to stars in the realm of Ideas to await planting in bodies created by the lesser gods to whom he assigned the task of making the sensible world. At the end of life, the rational soul returns to its domicile star if its human possessor had lived a good life; if not, the soul reincarnates in a lesser being. Our animal parts, the gift of the gods, serve merely to keep our head, the seat of our reason, from rolling around on the ground.

Used properly, our rational soul can bring us through observation of the motions of the heavenly bodies to the discovery of number, time, and harmony, and to the contemplation of the Ideas. We might then perceive that the Ideas of the four elements and the quintessence are linked to the mathematics of the five regular solids. The plane faces of three of them (the tetra, octa, and icosahedron) are equilateral triangles, and consequently the elements corresponding to them (fire, air, and water) are interconvertible (see Figure 2). The remaining two, the cube and the dodecahedron, are the "Ideas" of the earth and the universe as a whole. We should not press the obvious difficulties. The lesser gods who created the material world were not entirely competent. "[I]t is fitting that we should, in these matters, accept the likely story and look for nothing further."

Roman worlds

Although foreign students from Rome added little of note to Greek *physica*, they turned much of it into useful summaries and