The Story of Physics

Lloyd Motz

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Jefferson Hane Weaver

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Preface

The author of the story of a science must be guided by the constraints and demands imposed on him by the definition of "science" itself. A science is more than a body of knowledge expounded in original papers and collected in books; it is the active pursuit of this knowledge by a dedicated group of people (scientists) who are devoted to this "great adventure" by an inner drive that they cannot deny. Since physics as an intellectual activity is the search for the fundamental laws of nature, it is the basic science from which all others are derived; no phenomena in the universe are foreign to the physicist. But the physicist goes beyond the mere knowledge of facts because his ultimate concern is deducing from these facts basic laws that enable him to correlate what appear to be disparate phenomena and to predict future events. An excellent current example of this concern is the astrophysicist's description of the evolution of stars (for example, the sun) from their present states to their ultimate demise as white dwarfs, neutron stars, or black holes. The astrophysicist performs this task by applying the known physical laws to stellar interiors to discover their dynamic processes.

Since knowledge of natural phenomena or even of natural laws alone is not science, we have presented the story of physics here not only as the growth of a body of facts but also as the emergence and evolution of nature's laws from facts, which could have stemmed only from a remarkable intellectual synthesis of fact and fancy (speculation). In connection with this theme, we emphasize again the important distinction between knowledge and science. Every living thing in the universe, even a single cell, has the knowledge necessary for life, which is far beyond anything that we know consciously. Our eyes (or the cells in our eyes) know far more about the laws of optics than we do, and if we had to tell the organs in our bodies how to operate, we would quickly die. But despite all their cleverness, the cells in our bodies are not scientists, nor, as another example, are bees scientists, even though they know that they can keep their hives cool by rapidly vibrating their wings; they are arguably technicians, but not scientists.

Proceeding with this idea from cells, insects, and lower animals to ourselves, we note that each of us, even the most untutored in science, learns a great deal about the laws of nature without even being conscious of it. In walking, running, balancing ourselves, and avoiding all kinds of natural dangers, we constantly apply our subconscious knowledge of the laws of motion, the law of gravity, the laws of thermodynamics, vectorial concepts, and symmetry and conservation principles. Keeping in mind this distinction between knowledge *per se* and science, we begin our story of physics with the ancient Greeks, because their written records show that they were involved in the deliberate pursuit of knowledge (the beginning of science) as the pathway to an understanding of the universe. In that sense, and in accordance with our prescription, they were certainly scientists, although not very successful ones.

Since our book is not a history of physics, we do not explore all the facets of "Greek physics," but present only those salient features that influenced, whether in the right or the wrong way, the thinking of the scientists who followed. The discoveries of Pythagoras, Euclid, Archimedes, Aristarchus, Hipparchus, and Ptolemy are most notable in this respect, but to have done more than describe the works of these remarkable philosophers briefly, yet in sufficient detail to be understandable, would have expanded this book beyond its intended domain.

The reader who is not interested in the Greek contributions to physics can begin this book at Chapter 3, which deals primarily with the astronomical works of Nicolaus Copernicus, Tycho Brahe, and Johannes Kepler, whose derivation of the laws of planetary motion from Brahe's observational data is one of the great intellectual syntheses of the post-Copernican era. Comparing this achievement with that of the greatest of the ancient Greeks shows clearly the vast difference between the speculations of the Greeks (which were experimentally or observationally unsupported) and the sound observational basis of Kepler's deductions.

We single out Galileo Galilei's concept of inertia and Sir Isaac Newton's laws of motion for special emphasis because they are such a great departure from the thinking of the Greeks and the philosophies of the pre-Renaissance scholastics. This is most evident in the rapid post-Newtonian development of physics, which, in a relatively few years, laid the basis for all of classical physics and modern physics, even though modern physics, stemming from the quantum theory and the theory of relativity, departs drastically from Newtonian physics in certain fundamental features. However, the conservation principles, the symmetry principles, and the least action principles of classical (Newtonian) physics developed in the 18th and 19th centuries by the classical mathematical physicists were carried over to modern physics with certain crucial changes.

In our description of the development of classical physics, we emphasize such principles and show that they form the thread that connects one group of concepts with another (for example, the dynamics of particles with thermodynamics) and also define the continuity in the evolution of physics. Since this continuity is not broken by the rise of modern physics—that is, the quantum theory and the theory of relativity—we carefully show why the quantum theory was necessary and how it emerged from classical physics.

The transition from the quantum theory to the quantum mechanics (matrix mechanics and wave mechanics) as developed by Louis de Broglie, Erwin Schrödinger, Werner Heisenberg, Paul Dirac, and Max Born produced a much greater revolution in our thinking than did Max Planck's introduction of the quantum concept itself, for what that transition brought with it (that is, correctly predicted) was phenomena that defy physical understanding. We have therefore emphasized the physical features of the quantum mechanics as much as possible while pointing out the features that have to be accepted at this point without question.

Given the rapid development of high-energy particle physics during the last quarter of a century, no story of physics would be complete without a discussion, however brief, of the important theoretical and experimental features of current particle physics. We have therefore included a discussion of this topic in Chapter 19.

Lloyd Motz
Jefferson Hane Weaver

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CHAPTER 1

Greek Physics

Everything of importance has been said before by somebody who did not discover it.

—ALFRED NORTH WHITEHEAD

In writing a book that is not a history of physics but rather a story of the continuity of the ideas, observations, speculations, and syntheses that constitute the body of knowledge that we now call physics, we had to leave out aspects of this subject that rightly belong in a history. With this point in mind, we approached the Greek contributions to this story with the knowledge that whatever we included or did not include, the result would not be entirely satisfactory. Though Greek physics cannot be properly integrated into Newtonian physics, Greek philosophy and Euclidean geometry still influence our thinking; for this reason, we have included in this story of physics the features of Greek thinking that we believe to be pertinent to physics.

Physics, as we understand and practice it today, was unknown to the ancient Greeks, and we may speculate where society would be today if Newton's laws of motion and his law of gravity had been discovered by Aristotle or Archimedes. This is not to say that the Greek philosophers and mathematicians were not scientists in a very general and amorphous way; they were indeed, as evidenced by their keen observations of the heavens, their endless speculations, and their mathematical creations. Wherein, then, does their science differ from Newtonian science? Precisely in the absence of physical principles or laws that enable one to predict future events from current observations or, more generally, to correlate many apparently disparate phenomena in the universe.

A few examples will illustrate and illuminate this very important difference. No matter how much the Greek astromoners learned about the motions of the planets observationally, that information alone could not enable them to predict or understand the periodicity of the tides, the behavior of freely falling bodies, or the revolution of two neighboring stars (a binary) about a common point. Newton's laws, on the other hand, permitted him and the physical scientists who followed him to correlate and explain planetary motions, tides, and other phenomena as manifestations of the same physical force, namely, gravity. In the same way, without a deep understanding of pressure, the Greeks could not apply Archimedes's buoyancy principle to the explanation of general atmospheric phenomena as the Newtonians did. Greek science was thus entirely empirical and without basic laws.

But we still owe much to the ancient Greeks for their mathematics, their observational astronomy, and their range of speculations. Although mathematics is not physics, an important branch of mathematics, geometry, in which the Greeks were great experts, is so intimately related to physics that the study of Greek geometry is essential to the proper study of physics. Geometry is important to physics because the laws of motion of bodies can be only expressed in a geometrical context. This is also true of such phenomena as the spatial interrelationships of bodies and the empirical description of the motion of a body. If we had no geometry, we could not formulate physical laws that are useful precisely because they enable us to correlate disparate *spatial* events.

Today, we know that three kinds of geometries exist, Euclidean (flat space), hyperbolic (negatively curved space), and elliptical (positively curved space), but the Greeks knew only of Euclidean geometry, to which contributions were made not only by Euclid but also by Pythagoras and Eudoxus. Pythagoras (560–480 B.C.) founded a school of philosophers that lasted some 200 years and greatly influenced Greek thinking. Little is known about the details of Pythagoras's life, but he is believed to have spent much of his earlier years in Egypt and Babylonia learning mathematics. Forced to leave his lifelong home at Samos, he settled in Croton, Italy, in 530 B.C. and founded his school of philosophy. Although Pythagoras's teachings were influential throughout southern Italy, his antidemocratic views generated strong opposition that ultimately forced him to flee in 500 B.C. to Metapontum, where he spent his remaining years.

To the Pythagoreans, number was everything; they believed that all phenomena in nature could be explained in terms of numerical relationships, but they gave no recipe for discovering these relationships, and so their numerical philosophy was sterile. However, like all basic principles, the Pythagorean numerology had great heuristic value in that it prompted the Pythagoreans to seek symmetries and harmonies in all natural phenomena. This search led them to the discovery that the harmony of musical sounds depends on the regularity of the intervals between the pitches of harmonious sounds.

They generalized these ideas to propose a universal harmony to account for the apparent motions of the planets, which they associated with musical notes of different pitch. This theory, called the "harmony of the spheres," influenced even Johannes Kepler, who tried, in his early speculations, to represent the motions of the various planets by different octaves in the musical scale.

Today, Pythagoras is best known for his famous geometric law or theorem that expresses the length of the hypotenuse of a right triangle in terms of the lengths of the other two sides. This simple relationship, which Pythagoras established for a right triangle on a plane, has been generalized to any number of dimensions and to non-Euclidean geometry. So generalized, it is the basis of the geometrical interpretation of the laws of nature. Indeed, Pythagoras's theorem, in its most general form, is the starting point of Albert Einstein's general theory of relativity and all modern attempts to unify the laws of nature as manifestations of space–time geometry.

Euclid, of course, is famous for his *Elements*, contained in 13 volumes of definitions, postulates (axioms), and theorems, which summarize all the mathematical knowledge of ancient Greece. Its influence was tremendous, and Euclidean three-dimensional geometry was accepted, for hundreds of years, as the correct geometrical framework on which to formulate the laws of nature. Newtonian mechanics and James Clerk Maxwell's electromagnetism incorporated Euclidean geometry into their theoretical structures. The break with Euclidean geometry occurred when the great 19th-century geometers like Carl Friedrich Gauss, Nikolai Lobachevski, and Georg Riemann began to challenge Euclid's fifth postulate, which states that given a line and a point outside it, only one line can be drawn through the point parallel to the given line. The denial of this axiom led to modern non-Euclidean geometry, from which so much modern theory has evolved.

The vast difference between modern physics and Greek physics is perhaps best indicated by our present atomic theory and the Greek atomism that stemmed from Democritus and his school of philosophers. Democritus proposed the very attractive hypothesis that all matter consists of indivisible particles (atoms) differing in many ways (for example, in size, mass, color) that combine with each other to form all the matter we see in the universe. Since the Greek atomists gave no prescription or mathematical formulas for calculating any properties of matter or predicting any phenomena, their atomic theory remained useless and sterile.

On the other hand, modern atomic theory based on the electromagnetic interactions of the electrically charged constituents of atoms is a precisely formulated discipline that has evolved out of a synthesis of mathematics and basic physical principles. As such, it enables physicists to calculate atomic and molecular phenomena with incredible accuracy. The Greeks knew about electricity and magnetism, but they never connected electrical and magnetic phenomena with the atoms of Democritus.

Of all the Greek philosophers who concerned themselves with physical phenomena, Archimedes was the most notable and was the closest to what we now consider a scientist to be. Archimedes (287–212 B.C.), the son of the astronomer Phidias, was born at Syracuse and was good friends with King Hieron, the local ruler. He spent part of his youth in Egypt learning mathematics from the immediate successors of Euclid. He then returned to Syracuse, where he remained for the rest of his life.

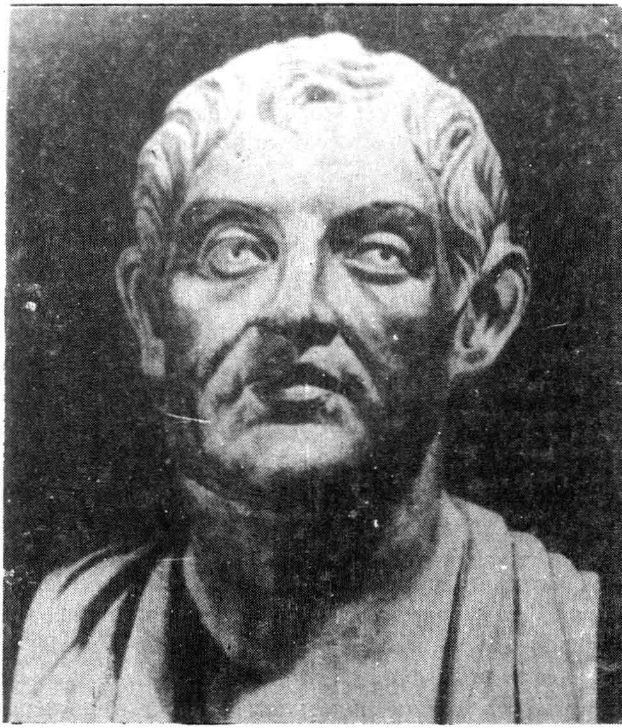
Archimedes combined theory and experiment in a manner similar to scientific procedure today, but no body of basic scientific principles resulted from his work. He attempted to do for science what Euclid had done for geometry: to show that scientific knowledge can be deduced as theorems from a set of self-evident propositions. But little is known about Archimedes's axioms or the theorems he deduced from them.

That Archimedes was a great experimentalist, an inventor, and a keen student of nature is indicated by his discoveries and his mathematical treatises. Not having a well-equipped laboratory to do actual experiments, he must have carried out the kind of thought experiments that characterize all great scientists. He is most famous for his discovery of the principle of buoyancy (the Archimedes principle), and he probably also knew the law of the spatial reflection of light from mirrors. His inventions ranged from the water screw to a planetarium and the astronomical cross-staff with which he made accurate celestial observations. He demonstrated his mathematical skill by showing how to deduce geometrically the number pi (the ratio of the circumference of a circle to its diameter) to any desired accuracy. He did this by approximating the circumference of a circle with the perimeter of a circumscribed or inscribed many-sided regular polygon. By allowing the number of sides to grow without limit and equating the perimeter of such a polygon to the circumference of the circle, one obtains an infinite series for pi.

Archimedes also wrote his *Sand-Reckoner* to demonstrate that very large finite numbers and the infinite itself are indeed different, as shown by the opening sentences: "There are some, King Gelon, who think that the number of the sand is infinite in multitude: and I mean by the sand not only that which exists about Syracuse and the rest of Sicily but also that which is found in every region whether inhabited or uninhabited. And again, there are some who, without regarding it as infinite, yet think that no number has been named which is great enough to exceed its multitude." Archimedes calculated how many grains of sand would fit in a poppy seed, then how many poppy seeds would be needed to equal the diameter of a finger, and so on out to a distance of some 10,000 stadia (one stadium is 607 feet) to arrive at the number of grains of sand he believed would be needed to fill the entire universe. More important than his ease in dealing with these large numbers was his classification of them by orders and periods.

Archimedes died at the age of 75 when Syracuse finally fell to Rome after a brutal siege prolonged by Archimedes's ingenious defensive devices. According to Herbert Westren Turnbull's book *The Great Mathematicians,*[1] the Roman commander, Marcellus, had ordered that Archimedes be taken alive because he "uses our ships like cups to ladle water from the sea, drives off our sambuca ignominiously with cudgel-blows, and by the multitude of missiles that he hurls at us all at once, outdoes the hundred-handed giants of mythology!" Although Archimedes's efforts in defense of his city were extraordinary, he saw them as no more than applications of mechanics, a subject that paled in importance in comparison with his beloved geometry. So devoted was Archimedes to his subject that when the city fell and the Roman legions were pouring through the breached gates, Archimedes continued to puzzle over a mathematical diagram drawn in the sand and was killed by a Roman soldier. Alfred North Whitehead viewed the death of Archimedes as a monumental event because "[t]he Romans were a great race, but they were cursed by the sterility which waits upon practicality." In Whitehead's opinion, "the Romans were not dreamers enough to arrive at new points of view, which could give more fundamental control over the forces of nature." In short, "no Roman lost his life because he was absorbed in the contemplation of a mathematical diagram."

We finally come to Aristotle (384–322 B.C.), Plato's most famous student, who predated Archimedes by some hundred years. Born in Stagira in Chalcidice, Aristotle's philosophy governed human thinking for nearly two millennia in fields ranging from physics and meteorology to biology and psychology. His father was the court physician at Macedon and probably contributed to Aristotle's early interest in biology and the



Aristotle (384–322 B.C.)

classification of sciences. Orphaned at an early age, Aristotle joined Plato's Academy in 367 B.C. and spent the next 20 years studying under the master, who "recognized the greatness of this pupil from the supposedly barbarian north, and spoke of him once as the *Nous* of the Academy—as if to say, Intelligence Personified."[2] After the death of his teacher in 347 B.C., Aristotle spent several years wandering among several of the nearby Greek kingdoms before returning to Macedon to tutor the young prince who would one day be known as Alexander the Great. After his return to Athens, Aristotle founded his school, the Lyceum, which attracted many students and—unlike Plato's Academy, which was devoted to mathematics and political philosophy—emphasized biology and the natural sciences.[3] Aristotle's belief that observation was essential to the study of science prompted him to collect "a natural history museum and a library of maps and manuscripts (including his own essays and lecture notes), and organiz[e] a program of research which *inter alia* laid the foundation for all histories of Greek natural philosophy, mathematics and astronomy, and medicine."[4] "If we may believe Pliny, Alexander instructed his hunters, gamekeepers, gardeners and fishermen to furnish Aristotle with all the zoological and botanical material he might desire; other ancient writers tell us that at one time he had at his disposal a thousand men scattered throughout Greece and Asia, collecting for him specimens of the fauna and flora of every land."[5]

Aristotle viewed mathematics as the key to providing a model for organizing science. This impression was probably formed while he was at Plato's Academy, where mathematics and dialectic discussions geared toward examining the assumptions made in reasoning were most heavily studied. Aristotle viewed the structure of science as "an axiomatic system in which theorems are validly derived from basic principles, some proprietary to the science ('hypotheses' and 'definitions,' the second corresponding to Euclid's 'definitions'), others having an application in more than one system ('axioms,' corresponding to Euclid's 'common notions')." His attempt to use mathematics as a tool for generalization, however, necessitated that the dialectic so favored by Plato be assigned a supporting role, to be called forth when mathematics could not free science of its regress and circularity.[6]

Although Aristotle is deservedly praised for his classification system, which exercised such a strong influence on the development of biology, his contributions to physics were undistinguished. His *Physics* was something of a metaphysical mishmash that purported to grapple with so-called "ultimate topics" ranging from infinity and time to motion and space. It did provide a valuable historical record because Aristotle recounted the views of earlier pre-Socratic philosophers. However, his purpose was not so much to call attention to the contributions of his predecessors as to enable him to refute and disparage their opinions. While *Physics* offered little in the way of astronomical knowledge and explicitly rejected the Pythagorean belief that the sun is at the center of the universe, Aristotle's meteorological speculations about the continual process of change in the world were inspired: "[T]he sun forever evaporates the sea, dries up rivers and springs, and transforms at last the boundless ocean into the barest rock; while conversely the uplifted moisture, gathered into clouds, falls and renews the rivers and the seas."[7] However, Aristotle was unable to synthesize his observations, discern underlying patterns in nature, and thereby formulate a useful theory about the physical world.

He did try to develop a theory of motion that would explain the kinematical behavior of all observable objects from the stars down to terrestrial bodies. He was misled in his analysis of the motions of bodies by his belief that a body can be kept in motion only if the body is in direct contact with a "continually operating mover." If the mover did not maintain contact with the body, the body stopped moving instantaneously; Aristotle had no notion of the concept of inertia, so he failed to discover the laws of motion.

To explain why phenomena happen, Aristotle introduced his doctrine of causes, which reduced all causes to four basic ones that he labeled "material," "formal," "efficient," and "final." We mention these labels here merely to show how far removed Aristotle's thinking was from the modern concept of causality. That Aristotle was a keen observer is evidenced by his geological discoveries and his biological classification schemes. These contributions are still noteworthy and valid.

Taken as a whole, then, Greek physics is not very significant; its greatest value lies in demonstrating how fruitless a putative exact science is if it does not have a sound theoretical foundation supported by a powerful mathematics. The Greeks discovered many interesting facts about nature, but their science did not progress because they had no principles to guide them in constructing a science with its own seeds of growth. We believe, however, that we can learn something important from the Greeks, for modern physics is in danger of developing into a body of theories without facts. Though the Greeks had no mathematical formalism to develop a strong theoretical base for their physics, they were ingenious and clever in their speculations. Today, something similar prevails in the most advanced stages of physics; elementary particle physics is drowning in a sea of formalism. Paper after paper, each with a welter of recondite mathematical equations, but with no numerical deductions, appears in the most prestigious journals of physics today. The absence of numbers at the ends of these papers is a clear symptom of the ill health of theoretical physics today, for it shows that theoreticians are discussing a fanciful universe, rather than the real one.