A History of Physics from Antiquity to the Enlightenment

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By

Mario Gliozzi

Edited by Alessandra Gliozzi and Ferdinando Gliozzi

Cambridge Scholars Publishing

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This book first published 2022

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-5275-8076-8
ISBN (13): 978-1-5275-8076-3

TABLE OF CONTENTS

Foreword xii

1. CLASSICAL ANTIQUITY 1
1.1 - Pre-Hellenic civilisation 1

THE HELLENIC AGE
1.2 - The pre-Socratics 2
1.3 – Aristotle 7
1.4 - Criticism from the disciples.. 12

THE HELLENISTIC AGE
1.5 - The Museum of Alexandria... 13
1.6 – Archimedes 14
1.7 - Alexandrian mechanics 19
1.8 – Philo 19
1.9 – Hero.. 21
1.10 - Greek optics 24
1.11 - Euclidean optics 25
1.12 - The optics of Ptolemy 27
1.13 - Hero's catoptrics.. 29

THE GRECO-ROMAN AGE
1.14 - Decline of Hellenistic science 29
1.15 - The Romans.. 30
1.16 - The Encyclopedias.. 30
1.17 – Philoponus.. 32

2. THE MIDDLE AGES 33

MECHANICS
2.1 - Arab mechanics.. 33
2.2 - Cultural reawakening in the West 34
2.3 - Medieval statics.. 35
2.4 - Dynamics in the Paris school... 37
2.5 - Dynamics in the school of Oxford 38
2.6 - Diffusion in Italy of the dynamics of Paris and Oxford.................... 39

OPTICS
2.7 – Alhazen 40
2.8 - al-Haytham's work in Western culture 45
2.9 - Roger Bacon 46
2.10 - Lenses and spectacles 47

MAGNETISM
2.11 - The compass 49
2.12 - Pietro Peregrino 52

TECHNICS
2.13 - Influence of Renaissance technics on the rebirth of physics 54

3. The Renaissance 58

LEONARDO DA VINCI
3.1 - Leonardo the inventor 58
3.2 - Hydraulics and hydrostatics 59
3.3 - Human flight 60
3.4 - Centres of gravity 62
3.5. – Statics 63
3.6 – Dynamics 64
3.7 - Pneumatics, optics and acoustics 65
3.8 – Method 66

16TH CENTURY
3.9 - The cultural environment 68
3.10 - Occult sciences 69
3.11 - Giovan Battista Porta 71

MECHANICS
3.12 - Nicolò Tartaglia 75
3.13 - Girolamo Cardano 80
3.14 - Giovan Battista Benedetti 83
3.15 - Simon Stevin 86

OPTICS
3.16 - Francesco Maurolico 88
3.17 - The invention of the telescope 92

MAGNETISM AND ELECTRICITY

3.18 - Magnetic declination and inclination *98*
3.19 - The first Italian treatise on magnetism *99*
3.20 - William Gilbert *100*
3.21 - The birth of electrology *102*
3.22 - Francis Bacon *104*

4. GALILEO GALILEI **107**

GALILEO AT THE PISAN STUDIUM

4.1 - Early years, isochronism of pendular oscillations *107*
4.2 - Early works *108*

GALILEO IN THE STUDIUM OF PADUA

4.3 - The science of mechanics *109*
4.4 - The thermoscopic experiment *111*
4.5 - The reinvention of the spy-glass *112*

GALILEO IN ARCETRI

4.*6 - Conditions of floating and the weight of air* *114*
4.7 - Science and faith *116*
4.8 - Il saggiatore (The Assayer); primary and secondar qualities *118*
4.9 - Dialogue Concerning the Two Chief World Systems *119*
4.10 - The Second Trial *121*
4.11 - The "Discourses and Mathematical Demonstrations Concerning the Two New Sciences" *123*
4.12 - The speed of light *124*
4.13 - Pendular motion; acoustics; last works *125*

GALILEAN DYNAMICS

4.14 - The principle of relativity *127*
4.15 - The principle of inertia *128*
4.16 - Free-falling bodies *129*
4.17 - Instantaneous speed/velocity *131*
4.18 - The composition of motion; motion of projectiles *133*
4.19 - The method *134*

5. In a New Furrow **136**

THE SCIENTIFIC CLIMATE
5.1 - The Galilean message *136*
5.2 - Evangelista Torricelli *137*
5.3 - For and against Galilean dynamics *140*
5.4 - Galilean philosophy in France *142*

PRE-NEWTONIAN MECHANICS
5.5 – Descartes *143*
5.6 - Descartes' "Laws of Nature" *146*
5.7 - Gravity according to Descartes *151*
5.8 - Cartesian mechanism *154*
5.9 - Giovanni Alfonso Borelli *155*
5.10 - Pierre Varignon *158*
5.11 - Laws on colliding bodies *161*
5.12 - The pendulum clock *165*
5.13 - Christiaan Huygens *168*
5.14 - The argument over life force *175*

FLUID STATICS
5.15 - Fluid pressure *179*
5.16 - Concept and measurement of atmospheric pressure *180*
5.17 - Pascal's principle *185*
5.18 - The pneumatic machine *186*
5.19 – Boyle's Law *189*
5.20 - Altimetric formulae *193*
5.21 - From the elasticity of air to the elasticity of solids *193*

THE ORGANISATION OF RESEARCH
5.22 - Academies and scientific periodicals *196*
5.23 - The Academy of the Lincei *196*
5.24 - The Academy of the Cimento *198*
5.25 - The Royal Society of London *201*
5.26 - The Académie des Sciences of Paris *202*
5.27 - The academies of Berlin and Saint Petersburg *202*
5.28 - Scientific journals *203*

OPTICS
5.29 – Kepler *206*
5.30 - The law of refraction *210*

5.31 - Theoretical research into lenses *216*
5.32 - Construction of optical instruments *220*
5.33 - Fermat's principle *223*
5.34 - Diffraction and the nature of colour *229*
5.35 - Double refraction and speed of light *235*

MAGNETISM AND ELECTRICITY
5.36 - In the footsteps of Gilbert *238*
5.37 - Guericke's experiments on electricity *240*

6. ISAAC NEWTON 242
6.1 - *The man* *242*

MECHANICS
6.2 - "Regulae phisophandi" *245*
6.3 – Mass *247*
6.4 – Force *251*
6.5 - Time and space *252*
6.6 - The Laws of Motion *254*
6.7 - Centripetal motion *255*
6.8 - Fluid mechanics *257*
6.9 – Acoustics *258*
6.10 - Confutation of Cartesian vortexes *260*
6.11 - Digression on the concept of attraction *261*
6.12 - The system of the world *264*
6.13 - Acceptance of the "Principia" *268*

OPTICS
6.14 - The mirrored telescope *270*
6.15 - The treatise on optics; definitions *273*
6.16 - Dispersion of light and the nature of colour *274*
6.17 - Research into dispersion *276*
6.18 - The theory of colours *278*
6.19 - "Rings", thin layers and absorption *279*
6.20 - Diffraction and double refraction *282*
6.21 - Corpuscular theory *284*
6.22 - The "Questions" *286*
6.23 - Microcosm, cosmogony and methodology *288*
6.24 - Huygens' wave theory *291*

7. The Eighteenth Century 297

THE SCIENTIFIC ENVIRONMENT
7.1 - The spread of Newtonianism 297
7.2 - Scientific dissemination 299

MECHANICS
7.3 - Living forces once again 301
7.4 - The Italian phase of the controversy 304
7.5 - From living forces to the parallelogram of forces 308
7.6 - Ruggero Boscovich... 312
7.7 - Analytical mechanics... 316
7.8 - Experimental mechanics 324
7.9 - d'Alembert's principle.. 333
7.10 - The principle of least action 334
7.11 – Acoustics 339

OPTICS
7.12 - The spread of Newtonian optics 343
7.13 - Achromatic lenses 347
7.14 – Phosphorescence 349
7.15 – Photometry 350

THERMOMETRY AND CALORIMETRY
7.16 – Thermometers 352
7.17 - The study of thermometric liquids 358
7.18 - Dilatometers and pyrometers 360
7.19 - The nature of heat and its measurement..................................... 363
7.20 - Phase transitions 371
7.21 - The measurement of heat and specific heat................................ 373
7.22 - Mathematicization of the fluid theory... 374
7.23 - Note on the introduction of the steam engine 378

ELECTRICITY AND MAGNETISM
7.24 - Phosphoric light; conductors and insulators; vitreous and resinous electricity 380
7.25 - The electrostatic machine and the Leiden jar 384
7.26 - Benjamin Franklin.. 387
7.27 - Electrical theories 391
7.28 - Giambattista Beccaria... 394
7.29 - Franz Ulrich Theodor Aepinus... 400

7.30 - The electrophorus *403*
7.31 - The electroscope *406*
7.32 - Measures of capacitance: Cavendish and Volt *409*
7.33 - Charles-Augustin Coulomb *418*
7.34 – Magnetism *427*
7.35 - Luigi Galvani *440*
7.36 - Alessandro Volta *445*

Bibliography 456

Index of Names 462

FOREWORD

Mario Gliozzi (our father) worked on *A History of Physics* right up to his death. To honour his memory, in 2005 we curated its posthumous publication by Bollati Boringhieri. The critical scientific and popular acclaim in Italy prompted us to suggest a version in English, to make the work available to a wider public. We also thought it opportune to complete the text with a final chapter illustrating the complex development of arguments, theories and experimental proofs that have characterised the *physics of fundamental interactions*.

The historian of science Mario Gliozzi was a pupil and friend of the renowned mathematician Giuseppe Peano, who bequeathed him his letters (subsequently donated by his children to the Library of Cuneo), some antique books and his library. As a pupil of Peano, Gliozzi was secretary of the Pro Interlingua Academy, coming into contact with the international historical-scientific world and being elected member of the *Académie internationale d'histoire des sciences.*

In one of his first research projects (presented by Peano to the Turin Academy of Sciences), Mario Gliozzi retraces the definition of the *meter* by Tito Livio Burattini. The 1934 work *"A History of electricity and magnetism from its origins to the invention of the battery"* won the Accademia dei Lincei prize and was the start of the *"History of electrology up to Volta"* issued in 1937. Gliozzi's historical studies comprise articles, treatises and anthologies of scientific writers.

The most challenging and certainly most stimulating work to which Gliozzi dedicated himself is, however, this "*A History of Physics".*

Before leaving the readers to judge the book for themselves, we would like to add a personal note about the author: Mario Gliozzi, our father. We have many childish memories of our family life, but one that, now we ourselves are old, is set in our minds: somewhere in the shadowed study of our old house in Turin, there was the continuous tack-tack of an *Olivetti Lettera 22,* proof of a dedicated and exemplary life.

The English translation is presented in two books. The present one "*A History of Physics from Antiquity to the Enlightenment*" has been translated by David Climie, M.A. Oxon (English Language and Literature). The second book entitled "*A History of Physics over the Last Two Centuries*"

has been translated by Jacopo Gliozzi, great-grandson of the author and PhD student in Physics at Urbana Champain University (Illinois, USA), who also added some updating notes; we warmly thank both for their invaluable contribution.

We are very grateful to our friends and colleagues, in particular to Prof. Matteo Leone, Prof. Roberto Mantovani and Prof. Clara Silvia Roero for advice and suggestions during the different phases of this work. Sincere thanks must also be extended to Prof. Vanni Taglietti, for his indefatigable and wide-ranging help in the realisation of the project.

Alessandra and Ferdinando Gliozzi

1. CLASSICAL ANTIQUITY

1.1 Pre-Hellenic civilisation

Driven by the demands of a hard life, primitive man, who made his appearance a million years ago, watched what wild animals were doing, tasted and tried vegetables, and looked for the best materials for his tools: stone, bone, wood.

In the Middle Paleolithic Age (200.000-30.000 B.C.), the first graffiti and the first burials appeared; in the Upper Palaeolithic (30.000-8.000 B.C.), the first sculptures and paintings; in the Mesolithic period (8.000-5.000 B.C.), domestication and breeding of animals, and the first attempts at cultivation occurred. Towards the end of the Neolithic Age (5.000-2.500 B.C.), man had become what we recognise now, and the Stone Age was succeeded by the Copper, Bronze and Iron Ages.

Over thousands of years, humankind was driven by need and a curiosity about nature, and gradually learned useful, and magical, techniques based on a wide understanding of zoology, geology, botany, medicine, astronomy, and mathematics. This raw knowledge, technology, and rites gave rise, at the start of the third millennium of the pre-Christian era to the first civilisations in the valleys of the Nile and the Euphrates. Egyptians and Babylonians reached their highest point in mathematics and astronomy. But the construction of the pyramids and the transport of the huge obelisks is also proof of a profound understanding of mechanics and statics.

The invention of baked bricks and the potter's wheel is ancient, dating maybe to before 3.000 B.C. The introduction of wheeled vehicles in the same period gave rise to what historians have called the "first industrial revolution". This was shortly followed by smelting and metal working, the use of oared boats and sailing boats, the introduction of the plough, scales, the lead line, the spirit level, the set square, dividers; in the second millennium, bellows, levers, wedges, winches, pulleys, siphons, and the water hour-glass were introduced.

Techniques that appear with the first organised civilisations and that were already tried and tested at the dawn of Greek civilisation include water supplies, irrigation and draining; transportation by land and sea; cultivation of food products (production of cereals, preparation of flour and bread, fermentation, and so on); the use of pigments and paints, introduced in ancient times more for their religious and esoteric significance than for their decorative effect; making and use of cosmetics and perfumes, often employed for hygienic and esoteric-religious purposes, and subsequently to make one look more attractive.

Some attempts to put this vast store of empirical knowledge into some sort of order can be seen with the Babylonians and the Egyptians: for example, starting from 2500 B.C., the introduction of fixed units of length, weight, capacity; recognition of the passing of the seasons; division of the year into months, days and hours. However, in general, there was still no sufficient evidence for a unitary collection of empirical knowledge in a single doctrine, founded on a philosophical conception of the world.

In the first millennium B.C., the civilisations of the Near East - Egyptian, Babylonian, Assyrian, Phoenician, Jewish - began to decline, while Indian and Chinese civilisations grew and, around the XV century B.C., developed in autonomy, seemingly without any contact with the Mediterranean cultures, whose heritage was adopted by the peoples living around the Aegean.

THE HELLENIC AGE

1.2 The pre-Socratics

The attempt to describe, co-ordinate, explain and predict natural phenomena, the first nucleus of what over the centuries would become physics (from the Greek Φυσις = nature) started in Greece in the VI century B.C., favoured by an advanced cultural environment and a language already refined by a long literary tradition.

The evolution of Greek science is usually divided into four periods: 1) the Hellenic era, from 600 to 300 B.C.; 2) the Hellenistic era, from 300 B.C. to the beginning of the vulgar period; 3) the Graeco-Roman period; 4) the period of the spread of Greek science to the Muslim and Christian worlds, up to the “renaissance” of philosophy and science in the XIV-XV centuries.

***The Ionic school* -** According to Aristotle, the first attempt at a scientific system was made in Mileto, on the Western coast of Asia Minor. Thales (appearing in 585 B.C. - that is when he reached maturity, that Greeks reckoned at 40) and Anaximander (570 B.C.) and Anaximenes (546 B.C.) asked what was the “primogenial matter”, the origin of all the changing things that the world present us with.

Thales believed it was water, perhaps because of biological considerations or perhaps because water was the only substance then known that existed in three different states: solid, liquid, gas. Anaximenes believed air to be the principle for all things and Anaximander believed in something indefinable, something "with no limits".

Asking these questions shows the replacement of magical-esoteric interpretations of natural phenomena, typical of primitive man, with a rational mentality that searches for a reason for change that is not supernatural. Reasoned answers to a question, that continue to our times, imply two common concepts, that should be highlighted: reduction of a maximum of phenomena to a minimum of principles; conservation of the matter, that even while assuming diverse forms, remains constant.

This continuous change, this eternal turnover of all things was re-affirmed by Heraclitus (c. 540-80 B.C.), aristocratic, sombre, scornful and contemptuous philosopher who believed fire to be the primal element.

The Pythagorean school - The political situation forced the philosophers to flee from Asia Minor to the Greek colonies in Sicily and southern Italy. One of the political exiles was Pythagoras, who left his native Samos and, after a long voyage, arrived in Crotone, on the Calabrian coast on the Ionian Sea. Here, he founded a school, known as the *italica* or *pitagorica* school. Some believe him to be a legendary figure and even Aristotle always refers to "pythagoreans" and never Pythagoras.

The pythagoreans taught that nature was in eternal motion and return: everything changes and nothing dies. The principle for all things is not this or that element, but the number. The claim would seem to mean that all matter is composed of physical points - the *monadi* – indistinguishable from each other, but whose numbers and configurations are the cause of the different properties of bodies. Thus, qualitative differences are traced back to quantitative differences, as Aristotle showed, although he criticized the theory.

Numbers assumed a fundamental importance in the construction of the world and gave rise to the especial interest in the study of its properties, the search for analogies and the related sense of mysticism.

The mystical quality of numbers led the pythagoreans to the study of musical chords. Philolaos (flourishing c. 400), the first pythagorean of which some fragment is preserved, carefully analysed the octave, to which he gave the term "harmony" (that originally meant "ideal agreement of numbers"). Although there exist various, and often contradictory, testimonies, perhaps the traditional attribution to the pythagoreans is not without foundation that credits them with experiments of sounds emitted by vibrating strings and the discovery that the highness of the sound depends (at the same tension) on the length of the strings. This led to argue that strings homogeneous and of equal tensions create a pleasant sound when their lengths are placed in simple numerical ratios.

The pythogoreans were the first to propose, against common acceptance, that the world and the other celestial bodies were spherical, perhaps justifying the hypothesis only on the basis that the sphere is the most beautiful and perfect solid shape. Philolaos first wrote a non-geocentric astronomical system, according to which Earth, other heavenly bodies and the "anti-Earth" rotate around a "*central fire*" that is invisible to us because it is at the opposite side of the inhabited world. The Sun, lit by the *central fire*, reflects the light received onto the Earth. The movements of the planets at different distances from the centre and at different speeds are compared to the vibrations of the strings, as their relative distances from the centre are in simple ratios, like the lengths of strings that produce pleasant sounds. This is the origin of the "music of the spheres", inaudible to mankind because it has heard it from birth: a poetical and mystical concept that fascinated later scientists right up to Kepler and beyond.

***The Eleatic school* -** The Eleatic school rose up against the belief in unceasing birth and death of all things. It opined it was an illusion and deception of the senses; the Eleatic school, in particular Parmenides of Elea (500 B.C.), initiated the distrust of the senses that did so much to hinder the progress of physics in following centuries.

The logical and mathematical parts of Parmenides were developed by his student Zeno of Elea, working around 440 B.C., whose paradoxes and "aporie" ("puzzlement" - *Achilles, arrow, stadium*) are famous and for a long time were used as evidence that he wanted to only to refute the movement; it is more likely that he intended, arguing against the pythagoreans, to affirm the continuity of time and space and the relativity of motion.

***Empedocles* -** Empedocles of Agrigento (c. 492-432) tried to reconcile Eleatic views with Ionic theories. He opined that the roots of nature are unchangeable, like the "being" of the Eleatics, but love unites them and hate divides them in a never-ending cycle, in the same way as the "becoming" for the Ionians.

Like the Eleatics, Empedocles believed that there is no birth or death; birth is union and death separation of the elements - fire, air, water, earth - the eternal elements, as each has its own nature, without changing from one to the other. They merge to create other substances: in the same way an artist prepares a few colours by mixing a little of that and more of that pigment to depict trees, men, fairs, birds, and fishes. A force, that Empedocles called "love", tends to unite the elements, while another, "hate", separates them. In terms of physics, it must be noted, in the Empedocles' system, in addition to the plurality of the elements, there is the introduction of two forces that we would call attraction and repulsion, at the root of natural phenomena and events.

According to Empedocles, air is a body, as water does not enter an upturned jug because of the compressed air. The Agrigento philosopher also opined that light was a "flowing substance" that, emitted from the luminous source, progressively reached the intervening bodies; in sum, light is corpuscular and moves at a finite speed. It may cross certain bodies because it passes through their pores contained in the granular constitution of matter. The pores, invisible because they are so small, are not totally empty, because a vacuum does not exist.

***Anaxagoras* -** Anaxagoras (c. 500-428 B.C.), a younger contemporary of Empedocles, also tried to prove the non-existence of a vacuum, identified with the pythogoreans' air, using Empodecles' jar and other air-filled vessels resistant to pressure. Contrary to Empedocles, Anassagora believed that matter was continuous and that the transmutation of substances was impossible: "How can a hair be generated from what is not a hair, or flesh from not is flesh?" he noted. He believed in the pre-existence of all things and their existence in different proportions in every spatial region. If a given substance appears in a given point, it only signifies that it is there in greater quantity. Similarly, when we eat bread and water these do not change into meat and blood, rather from bread and water separate the invisible particles of blood and meat that they contained and, reunited in large numbers, become visible to us as meat and blood.

***The atomists* -** In response to the Eleatics, Empedocles and Anaxogoras proposed different qualities of the matter. The atomistic school proposed a new solution: matter possesses no qualities, it is homogeneous, impenetrable, indestructible and discontinuous, therefore made up of parts that cannot be divided, thus called *atoms* (indivisible). Atoms are not the pythagorean equal "monadi" dispersed in the "pneuma" (air), but have different shapes and sizes, separated by an absolute vacuum.

Atomistic doctrine is linked to two names: Leucippus, a half-legendary figure whose actual existence is in doubt, and his pupil, Democritus, born in Abdera (Thrace) around 460 B.C. and died c. 370 B.C., of whom about three hundred fragments have survived.

According to Democritus, atoms are indivisible because of their hardness, not smallness, as there exist atoms as large as a world. They are made up of equal substance and differ by form and dimension and, in groupings, by order. Atoms are in perpetual motion in all directions and when they meet their innumerable combinations create all the bodies of infinite space (the infinity of space is explicitly postulated by Democritus). The sensitive qualities of our experience (heat, cold, sweet, sour, colour, sound, etc.) are subjective, depending on the individual experiencing them. They depend on the form of the prevalent atoms in each body, but the sensations produced also depend on the sentient subject so that the same atomic figure may have contrary effects and contrary figures may produce the same effect.

Weight and hardness, on the other hand, are real, therefore objective, qualities of the bodies. Democritus explained the varying macroscopic weight of bodies through they different mix of atoms and vacuum. However, one fragment that is not easy to interpret would seem to include in the explanation the different weight of the constituent atoms. The different hardness was explained by the different distribution of the atoms: in lead, for example, the atoms are distributed regularly and therefore lead is softer than iron where the atoms are distributed irregularly. It may be too much to claim, but simply an interpretation for our times, that for Democritus hardness was a property linked to the reticular structure of the material being studied.

Plato **-** Plato, born in Athens (or Egina) 427, died 347, is one of the world's greatest philosophers and writers. His place in the history of philosophy and literature is of great importance, but in the history of physics, he will be remembered as a retarding force of the development of this science, despite his undoubted merits in mathematics.

According to Plato, truth is to be found in the world of pure forms, in the reign of "ideas", eternal and immutable models that shape our world of shadows. In the *Timaeus* dialogue, he tries to give a true description of the creation of the world by a creator or divine "demiurge" that, looking at ideas, first creates the soul of the world and then gives it physical form: everything is given a determined mathematical shape (air is a regular octahedron, water is a regular icosahedron, and so on). Plato also believed in the four elements, but mixed this belief with a cloudy pythagorean mysticism whose physical meaning is difficult to understand. He tried to explain the origins of the world and natural phenomena regardless of the observation and experimentation, but applying a moral teleology, already adopted by the pre-Socratic philosophers, based on personal concepts of beautiful and good: the world was created for a specific purpose by an ordered mind.

More than for the ideas it expresses, the Timaeus is important as historical source of the scientific theories of the time, that we would not know otherwise.

1.3 Aristotle

A history of philosophy would demand a much wider description than our previous treatment of the philosophical schools and philosophers before Plato.

But, with rare exceptions such as the pythagorean research on vibrating strings, the tradition and documents passed down to us (evidence from pre-Socratic philosophers is fragmented and mostly derives from a few quotations from later writers) gives us no proof that Greek philosophers before Plato made physical analyses, that is the study of single phenomena and individual natural objects. On the contrary the pre-Socratics, with the fearlessness and freshness of youth, immediately launched themselves on the search for the material principle of all things, posing questions of cosmic physics that, due to ignorance of particular natural laws, necessarily assumed a metaphysical nature. Their doctrines, by consequence, concern the history of philosophy rather than the history of physics.

This historical view does not mean that we should ignore the importance of Greek philosophy in the first two centuries for the history of physics. The speculations of the philosophers of the Ionic school on the primitive element, Empodocles' poetic forces, the atomism of Leucippus and Democritus, Plato's animism will become the guidance and inspiration also for physicists when over time, as we will see in this brief history, there will be a search for a broader and not gratuitous understanding of particular phenomena.

But, precisely because of this function, the works of the early philosophical schools emerge as a cultural base, contributing to making sense and giving a purpose to scientific research, opening the way to scientific discourse, creating that framework of forms of expression, causal links, accepted and widespread mental attitudes at the heart of "common sense" and "good sense", that are neither "common" nor "good" absolutely, but are related to the cultural level of the people of a certain epoch.

If we had documentation, perhaps we would discover in the first two centuries of Greek philosophy traces of observations and experiments on particular phenomena and bodies. This supposition can be supported by the first major scientific system in history: Aristotle's nature books, included in a vast encyclopedia of knowledge that cannot be the work of a single man but the result of collaboration between many people or many generations.

Aristotle organised the exhaustive material under his genius, boiling it down to units, systems, that would be the framework for science for the next two thousand years.

Aristotle, born in Stagira, Thrace, in 384 B.C., was a pupil of Plato up to the latter's death; he then left Athens and travelled the Greek world; from 343 to 340 he was at the court of Phillip of Macedon, tutor of his son, the future Alexander the Great. In 335, he returned to Athens and found a School, the Lyceum, taking its name from the sacred gardens of Apollo Lyceum where it was built. He oversee the Lyceum for 12 years when, on the death of Alexander the Great, the anti-Macedonian reaction forced him into exile in the Chalcis, where he died in 322, aged 63.

Aristotle's dialogues have been completely lost but almost all his expositive essays have survived. The ones of particular interest for physics include the treatises: *Physica* (in 8 books), *De coelo* (4 books), *De generatione et corruptione* (2 books), *Meteorologia* (4 books), to which should be added *Problemata* and *Mechanica*, that is questions of mechanics, collections in the form of questions and answers, both almost certainly apocryphal.

Aristotle's naturalistic works order all contemporary physical knowledge, referring to and, if necessary, confuting earlier beliefs. Reacting against Pythagorean and Platonic mysticism, Aristotle attempted to base physics on observation and experimentation. Like Plato, Aristotle believed that sensible understanding of the particular is contingent, connected to time and space, while scientific knowledge is absolute, beyond the bounds of time and space. But our universal concepts do not come from reminiscence, as Plato taught, but through deduction from the particular to the general, starting with the experience of the senses: consequently, observing assumed greater importance in building up science, while mathematics became less important and was little used by Aristotle. But this naturalistic approach was subject to a more general teleological axiom that limited its fruitfullness: every event has a defined purpose and the whole universe is the result of a predetermined plan. The teleologic concept of the world, exasperated by Aristotle up to his acceptance of an "intelligent nature", was a cornerstone of his thinking and was a keystone in later interpretations of Aristotelian philosophy. Notwithstanding the criticism of Theophrastus (372-288 B.C.), Aristotle's most distinguished pupil, the teleologic axiom, that became foreign to our physical mentality, even though it gave a good outline for biological research, remained firm up to the beginning of the modern era and, on some occasions, peeps out today.

Aristotle maintained the four elements but rejected the Platonic correspondence to polyhedrons; they are not the elements of Empodocles, even though they have the same names: earth, water, air, fire. Aristotelian elements are made of a single primary matter that takes on different forms according to its various qualities: heat, cold, dryness, wet, that are present always in four pairs of cold-dry, cold-wet, hot-wet, hot-dry. When the primary matter is cold-dry it is earth, and water when cold-wet, air when hot-wet and fire when hot-dry. The elements may transmute circularly, that is according to the above succession that imposes cold-dry follows hot-dry.

Earth occupies its proper "place" at the centre of the world, coinciding with the centre of the terrestrial globe; water surrounds the earth; then there is air, finally fire. All four make up the sub-lunar world.

Above fire is the sky, made up of the fifth element -*ether*- suggested by Philolaus, perhaps due to the discovery of the fifth regular polyhedron (the dodecahedron). Ether is the perfect element, pure, everlasting, unchangeable and incapable of being recreated.

The world is unique, limited in space but unlimited in time, complete in itself and split into two areas obeying different laws: the sub-lunar world in which all things are born, decay ad die, the world of the stars unalterable and incorruptible. This distinction, surpassed by earlier philosophers is not merely "a priori" thinking nor a return to Pythagorean theory but rather the result of common observation of earthly transformations, especially meteorological phenomena, while not noting any change in the sky, although astronomical observations had been uninterrupted for centuries.

Of particular interest to us is the Aristotelian science of motion that, after having dominated physics for many centuries, was challenged from the Renaissance onwards. Aristotle's theory of motion is wider than that, after Galileo, we are used to. Aristotle interpreted motion as a quantitative or qualitative variation causing an event: this broad description meant he could claim that in nature everything is in movement. He called the limited change in the position of one body in relation to others over time *local motion* and within the "local motions" there were *natural motions* and *unnatural* or *violent* movements, thereby breaking up the continuity and homogeneity of the phenomena, whatever their natural or accidental cause. In short, the Aristotelian universe has two fractures: it is split spacially and it is split phenomenologically.

Aristotle classified motion as circular and rectilinear. The first is the most perfect while the second has two forms: away from the centre and towards the centre (light bodies rise, heavy bodies fall). Ether is a perfect body and therefore has a perfect circular motion, and because the heaven is made up of ether, it has a circular motion. The regularity and eternity of the motion of the stars, that Aristotle calls the *primo motore immobile*, needs to have a cause that impresses motion to all the spheres in which the stars are set. If the concept of p*rimo motore immobile* is certainly metaphysical, even theological, placing the Earth at the centre of the Universe corresponds to the need to prove the everyday experience of seeing the stars rotating around the Earth.

Rough observation also corresponds to the laws of natural motion of bodies in the sub-lunar world. Common observation gives us elements that fall and elements that rise (for example, smoke and fire): therefore, heavy bodies naturally return to their place of origin, the centre of the Earth, while lighter elements move upwards, that is towards the limits of the sub-lunar world. In any case each body, be it heavy or light, moves towards its natural place: "heavy" and "light" therefore become absolute concepts. In this way Aristotelian physics is an obstacle to the notion of specific weight, that emerged much later and only with Archimedes (§ 1.6).

Aristotle judged the non-vertical motion of projectiles to be violent and divided the trajectory into three parts: the first rectilinear and oblique, the third rectilinear and vertical, the second circular and raccording the two. This theory would last until Nicolò Tartaglia's *Quesiti et inventioni diverse* (1546).

But how, once thrown, does the object keep moving? The cause cannot be the object itself, nor the person who threw it and who has no further effect on it: it must be in the middle. Aristotle had a bizarre theory that the thrown object continued to be driven, like a sail by the wind, by the air occupying the vacuum left behind the object thrown as it moves.

This theory of dynamics is very different to ours. In Aristotelian dynamics, the body in motion is always the result of the force applied at that moment and is inversely proportional to the resistance of the medium. Consequently, in a vacuum, as there is no resistance, velocity would be infinite, meaning the body would be ubiquitous. The deduction goes so against common sense that Aristotle concluded that a vacuum could not exist in nature: a conclusion that was the exact opposite of what the atomists had arrived at, who believed that motion would be impossible in the full. Aristotle debated for a long time with the atomists about this and supported his theory with other topics: it cannot be explained why in the vacuum a body in motion would stop in one place or another, because in the space, as a vacuum, there is no difference, but one could say that in the space (vacuum) everything should be at rest as there would be no reason why a body should move in one direction or another, or at different speeds. To conclude, Aristotle's basic argument against the vacuum is that it cannot contain any spatial arrangement: no high, no low, no right, no left. Emptiness would be inactive and impassible; therefore, it does not exist in our limited world. This is clearly more an abuse rather a use of the principle of sufficient proof.

Starting from these considerations, Aristotle (*Physica, IV, 6-9*) -who defined place as the limit of the contained body and space as the place without a contained body but that could contain one– concluded that emptiness is a contradiction of logic, because it would create a *locus sine locato corpore* (place without a contained body): a senseless abstraction, as modern relativists would say in another way when they criticise absolute space to which the movements should refer.

Horror vacui will be a cornerstone of Aristotelian physics and the polemics between supporters of "vacuum" and supporters of "fullness" continued up to the scientific renaissance (and maybe beyond, with the arguments over ether). But, to hear a new opinion on the physical question, we must move on to Torricelli's experiments in 1644 (§ 5.2).

Some historians have claimed to find in the Aristotelian anti-vacuum argument the principle of inertia. However, the chapter of *Physica* (IV, 8 215-19) in which the principle is to be found is used as a proof of the absurdity that would be reached with admitting emptiness (vacuum), Aristotelians in later centuries interpreted the chapter in this way. The chapter therefore confirms that the principle of inertia was completely unknown to classical science, that thought it absurd.

Another immediate consequence of Aristotelian dynamics is that the velocity at which a certain body falls is proportional to its weight (this seemed to be proved by the common observation that an apple falls faster than a leaf). On the other hand, careful and prolonged experiments arrived at the acute observation of a constant increase in the velocity of falling bodies, that Aristotle attributed to a gradual increase of the weight of the bodies that go getting closer to their place of origin. Another great merit of Aristotelian kinetics is the exact description of the rules of the composition of displacements, albeit for the particular case of perpendicular displacements.

Although it is very different from ours, Aristotle's interpretation of dynamics should be recognised as a great merit. He was the first scientist to advance a coherent semi-quantitative theory, in a field that was so difficult that it took another fifteen centuries before a new science took its first tentative steps.

The study of statics is closer to modern research: it expounds the theory of equilibrium in a lever, with an anticipation of the later principle of virtual workings, and a description of weight scales and pulleys.

The works of Aristotle, and especially the *Problems*, contain numerous interesting comments on music, meteorology, physics, and applied mechanics; references to kinetic energy, observations on osmosis, correct ideas on sound propagation in air, explanations of echo as reflection, a similar (but erroneous) explanation of rainbows, comments on the propagation of light, and so on. It is a highly commendable collection of observations that confirm how Aristotelian physics was based on observation, albeit ingenuous, and partly on experimentation, even if primitive.

What is missing in the Aristotelian physics, apart from the incapacity to separate single phenomena from their natural processes, is analysis, a critical eye and a wariness of generalisation.

We may claim that modern science experiments with a critical approach while Aristotelian science experimented ingenuously. In plain terms, Aristotelian mechanics did not distinguish passive resistances and he did not understand that the study of certain phenomena sometimes requires some "trick" that goes beyond mere observation. Naturally, this does not explain the Aristotelian failure in the study of physics, but is a comment on the insufficiency of his research methods. On the other hand, an explanation of why Aristotle and his school did not know how to make abstract, in the above sense, is an old and still unsolved question.

1.4 Criticism from the disciples

Aristotle's theories of physics were not immediately or generally accepted. It was only after 500 years that Alessandro d'Afrodisia, c. 200 A.C., expressed appreciation for his physical theories. Theophrastus (372-287 B.C.), Aristotle's successor as head of the Lyceum from 322 up to his death, gave a decidedly scientific character to the School and pursued the indications if his teacher in botanical studies. However, in physics he raised the first objections to finalism, the radically different nature of the motion of heavenly bodies to terrestrial movement, and the theory of the elements, from which he excluded fire.

Theophrastus's cautious critique was deepened by Strato of Lampsacus (d. 240 B.C.), called *the physicist,* who succeeded him as head of the School until 269. Strato preferred the study of particular physical phenomena over the grand summaries of cosmic physics of his predecessors, at least judging by the pneumatic experiments attributed to him by Hero. Unfortunately, only a fragment of his vast scientific work has come down to us, aside from the reports of later writers.

In the treatise (lost), *De vacuo*, Strato, while refuting the infinite vacuum of Democritus, admits, unlike Aristotle, the existence of small empty spaces inside matter, the *vacuum intermixtum,* or disseminated vacuum as Hero would call it. He did not accept the atomic theory, and also criticised Aristotle's theory of the elements, particularly the concept of the *natural* *places* of the elements and the consequent idea of absolute lightness and weight: every body, including fire, has weight, and the rising of light bodies is not due to a natural trend but the driving force of air. In a more radical criticism than that of Theophrastus, Strato opposed Aristotelian finalism, claiming that physical phenomena are the result of mechanical causes, not finalistic causes.

THE HELLENISTIC AGE

1.5 The Museum of Alexandria

The century before the death of Strato witnessed enormous political changes that had a profound effect on Hellenic culture. With victory of Phillip of Macedonia at the battle of Chaeronea (338 B.C.), the cities of Greece lost their freedom. Shortly after, Alexander the Great conquered the Persian empire in a flash, and founded military agricultural colonies, some of which soon became important commercial centres. The most illustrious city founded was Alexandria.

On the death of Alexander (323 B.C.), and the flight of Aristotle, Athens was no longer politically important and was also losing its intellectual supremacy. The schools of philosophy remained, but with the separation from sciences, were impoverished and increasingly concentrated exclusively on moral questions.

The scientific movement, promoted by the general use of Greek and the generous patronage of princes of regions resulting from the breakup of the Alexandrian empire was, at this point, so far advanced that science could no longer belong to the general public, but only limited to specialists. In the shadow of the thrones, scientists, honoured and generously rewarded, produced the best of antique science.

Some cities, like Syracuse and Cos, that already had a cultural tradition in the Hellenic age, gave a new impetus to scientific studies. Alongside these, scientific centres were added: Pella in Macedonia, Antioch in Syria, Pergamum in Asia Minor, and, later, Rhodes, Smyrna, Ephesus and so on: all took as their model the important institutions established in Alexandria that remained throughout antiquity the scientific capital of the Graeco-Roman world.

Ptolemy I Soter, the founder of the Ptolemaic dynasty in Alexandria, summoned to his court Demetrius Phalereus, who had been a pupil of Aristotle, and later, as a tutor of his son, Strato of Lampsacus. Demetrius was ordered to construct a school along the lines of the Lyceum and subsequently laid the foundations for the two cultural institutions in

Alexandria: the Museum, named in honour of the Muses, and the connected library, the core of which seems to be a collection of the works of Aristotle. With Ptolemy II (Philadelphus), who succeeded in 285 B.C., the Museum became an important cultural centre where intellectuals could live together paid by the state, and with access to two huge libraries, that in 48 B.C. held seven hundred thousand texts. This was the first example of a collective organisation of scientific research and we have to wait until the 20th century to see its imitation. Very soon, books began to be published by the Museum, thanks to the Egyptian *papyrus*, that gave Egypt a natural monopoly of the production of paper.

These extraordinarily favourable conditions for academics attracted numerous scientists to Alexandria from all over the world, giving rise to scientific schools that would continue throughout antiquity. More specifically, all the physics of the Hellenistic age, that constitutes classical antiquity's greatest and best contribution to the study of nature, is linked to the Museum of Alexandria.

1.6 Archimedes

Archimedes is also linked to the fortunes of the Museum; his work clearly demonstrates the contrast between the great philosophical syntheses of the Athens School and the systematic scientific research of particular natural phenomena instituted by the Schools of Alexandria.

Born in Syracuse, perhaps in 287 B.C., Archimedes studied for a long period in Alexandria under Phidias, the famous astronomer, and for the rest of his life kept up relations with the scientists of the Museum. In Egypt, perhaps on a second visit, when he was already famous, it seems he built bridges and dams to check the flooding of the Nile. But his most ingenious invention in this period was the *cochlea*, now known as *Archimedes' Screw* (Fig. 1.1) that, in the opinion of Galileo, an expert and severe judge, "is not only marvellous, but miraculous, because the water rises in the screws by falling continuously"[1]. The invention, the result of Archimedes' knowledge of geometry and constructed thanks to his exceptional ability in mechanics, was used by the Egyptians both to bring water to high lands (maybe up to 4 metres) that were not naturally affected by the floods and to drain low-lying areas.

[1] Galileo Galilei, *Mechanics*, in Id. *Works*, Ed. Nazionale, Barbera, Florence 1890-1909, Vol. 2, p. 186.

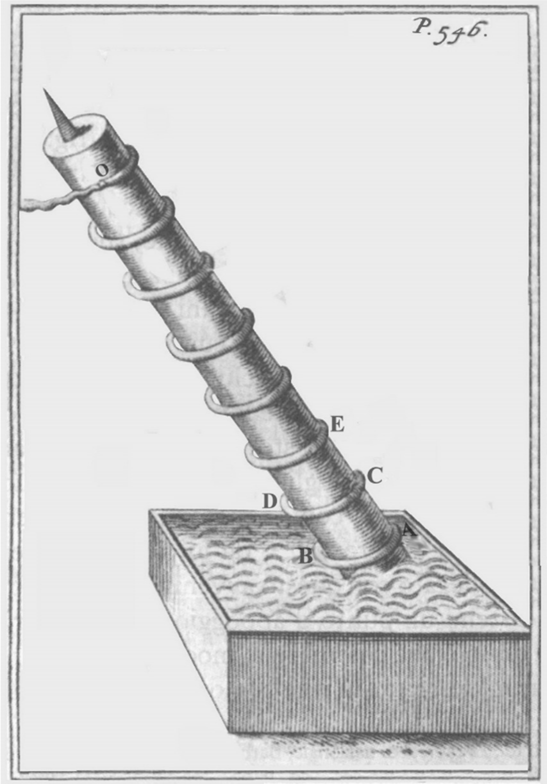

Fig. 1.1 - Archimedes Cochlea in an early 18th-century *Dictionnaire de mathematique*

But there are at least another forty mechanical inventions credited to Archimedes, and although historical sources are part of legend, historians have no doubt about some of them, such as the worm / gear wheel and differential hoist that he used to launch a large ship. This event is linked to what he is supposed to have said: “Give me a fulcrum and I will lift up the world”. Undoubtedly, he created that precision mechanics model: the planetarium, described in a lost work; Marcellus brought it to Rome as a trophy of war and Cicero later admired it. Last, there is no doubt about the legend of his defence of Syracuse during the three-year siege of the roman army, commanded by Marcellus, employing a number of weapons that terrified the besiegers. In the end, Syracuse was conquered (212 B.C.) and, against Marcellus’s orders a stupid Roman legionary murdered Archimedes while he was drawing on the sand: even if the story is not true, it is fitting.

Archimedes was the founder of statics and hydrostatics. Even though his writings are in the form of geometric expositions, based on postulates derived from experiments that he does not describe, it is certain that he carried out precise experiments. Archimedes himself wrote about one which he did to measure the angle of the apparent diameter of the Sun: "After having paced a long ruler on a vertical support, and placed where sunrise could be observed, a small lathed cylinder is positioned vertically on the ruler. When the Sun appears on the horizon and becomes visible to the eye, the ruler is turned towards the Sun and its ends observed; in the meantime, the cylinder, positioned between the Sun and the eye, completely obscures the Sun. Then, the cylinder is gradually moved away from the eye until the Sun begins to appear in each part of the cylinder, and is then fixed"[2]. Modern physicists cannot describe the experiments more accurately.

The first scientific work of Archimedes seems to have been on centres of gravity, in which he deals with the principles of lever and centres of gravity or barycentres. The condition of equilibrium of a lever can already be found in the mechanical theories attributed to Aristotle, as already mentioned, but these were unclear and mixed with ideas on dynamics. Now, Archimedes arrived at his conclusions from experiments on real levers, as it is obvious that his postulates on the equilibrium of levers are the result of experimentation. The first, and fundamental, theory is: "Let us suppose that equal weights positioned equidistantly remained balanced. Equal weights placed at different distances are not balanced, but (the system) goes down towards the weight furthest away"[3]. In Proposition VI, he deduces: "Commensurable weights will be in equilibrium if the distances at which they are suspended are in inverse proportion to the weights"[4] and in the next Proposition he extends that property to include non-commensurable weights.

This text contains a fundamental concept of mechanics: the centre of gravity. Propositions 4-7 describe it without defining it. We may suppose, therefore, that the concept was introduced by some unknown predecessor of Archimedes and by he himself in some now lost work. But in either case, Archimedes must be recognised as the founder of the rational theory of barycenters.

This concept is also linked to the discovery of another fundamental concept of mechanics: the moment of a force with respect to a straight line

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[2] Archimedes, *Arenarius*, I, 12, in *Archimedes opera omnia*, Greek text and facing Latin translation, edited by J.L. Heiberg, Teubner, Lipsia, 1881, Vol. 2, p. 251.

[3] Archimedes, *De planorum equilibriis, svie de centro gravitatis planorum,* I,1, in *Archimedis opera omnia*, op cit, Vol. 2, p. 143.

[4] *Ibid*, p. 153.