A Brief History of Science
Part-2: The Upsurge of Greek Intellect

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The advent of the iron age saw large-scale warfare and redistribution of the empires. Out of the ashes of that chaotic period sprang a civilization that was to have enormous influence on the intellectual development of mankind. It happened in a land somewhat removed from the older civilizations like Babylon, Egypt, Persia, India, etc., to be free from the conservative influences. On the other hand it was not too isolated, so that it could adopt and build on the knowledge created in those cultures.

A few factors were responsible for this great intellectual upsurge. By the time of the advent of Greek civilization, slavery had taken roots in the society. As a result of that, for the first time, some people—the slave owners—had free time to engage in thinking alone. By then quite a few scientific and technological advancements had happened (for example, wheel, pottery, metallurgy, astronomy, number system etc.). The Greeks built on that ground, and took it to a far higher level of abstraction.

Secondly, for most part of the Greek civilization, there was no large monarchy (the first Greek empire was built by Alexander, which disintegrated after his death). The Greek society was mostly centred around small city-states, where the separation between the ruler and the ruled was rather small. As a result, most citizens were able to take part in political life. In most of the city states there was no king, and a council of citizens took the political decisions. As a result of this political environment, great importance was attached to one's ability to argue. The cultivation of logic had its impact on the way the Greeks tried to answer questions that naturally came to their mind.

The historians divide the Greek period into three phases: the Ionian phase, the Athenian phase, and the Hellenistic phase—each with its characteristic social factors and contributions to science.

The Ionian period

The first burst of intellect happened in the sixth century BC, not in the mainland Greece, but in the cities of Asia minor and the islands in the Mediterranean sea, populated by Greek people. Trade routes established a link between these cities and the older civilizations, and at the same time these cities were not rich enough to be target of invasion. Thus shielded, the Ionian Greeks of these city-states started building on the science and technology of the earlier cultures.

The first spark was ignited by Thales (624-547 BC) of Miletus (a coastal city in West Asia), which was followed by people like Anaximander (610-545 BC), Anaximenes (585-528 BC), Pythagoras (572-497 BC), Empidocles (494-434 BC), Hippocrates (460-370 BC), Archytas (428-

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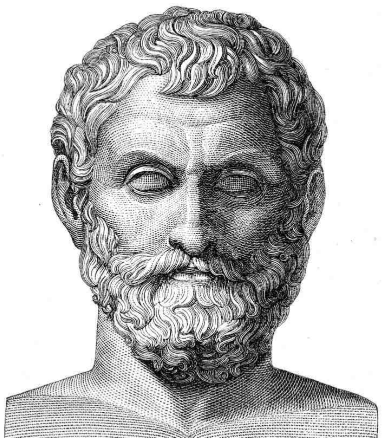
Map of ancient Greece

347 BC), etc. Their tendency was towards giving a theoretical structure to the science and technology developed till that time.

The people of Egypt had built the pyramids; but **Thales** invented a method of measuring the height of a pyramid based on geometry. Traders and sailors had travelled to distant lands; but **Anaximander** (610-545 BC) was the first to put together a map of the then known world based on the accounts of travellers and sailors. The ancients knew the construction of a cube; but **Archytas** (428-347 BC) solved the problem of building a cube twice the volume of a given cube. From these, one can easily see the inclination towards developing a theoretical solution to a given problem.

That tendency of abstract thinking was taken to an altogether different height by **Pythagoras** (572-497 BC), the man famous for his "theorem". He founded a brotherhood of mathematicians who practised mathematics as a secret sect, keeping their findings within themselves (we know about the work of the Pythagoreans through the writings of a later mathematician, Philolaus). They worked with numbers and found many of their properties now known in number theory. For example, they identified 1,3,6,10,15 etc. as "triangular numbers" and 1,4,9,16,25 etc. as "square numbers" (you can form a triangle with 10 dots and a square with 16) and proved that two consecutive triangular numbers give a square number. By analyzing the length of the hypotenuse of a right-angled trian-



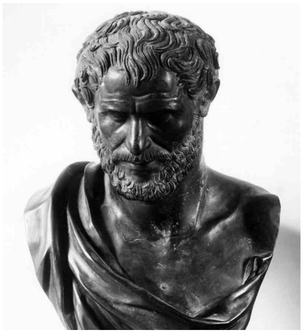
Thales of Miletus (624-547 BC)

gle of side 1 (which is $\sqrt{2}$), they came to the conclusion that all numbers cannot be expressed as ratios of integers, and gave birth to the concept of irrational numbers. In fact, it was the Pythagoreans who developed the method of deduction from known "axioms" which is at the basis of much of mathematics even today. One of the major contributions of the Pythagoreans is to demonstrate the relationship between music and numbers: The notes Sa, Re, Ga, Ma etc. (of the Indian system) on a string instrument always occur in whole-number ratios of the lengths. In spite of such great contributions, their work had a mystical character: they attached mystic properties to numbers, each number having a specific character. They analyzed various geometric shapes and concluded that the circle and the sphere are the most "perfect" shapes. That led to their belief that all celestial objects are spheres, moving in circles. They pictured the universe and the movement of the celestial objects as a "harmony of numbers" much like the harmony in music.

One of the basic issues that pervade much of Greek philosophy concerns the question: What is everything made of? **Thales** thought that water is the basic constituent of the world; all the things we see around us emerge out of water and in the end go into the water. In contrast, in the view of **Anaximenes**, air is the basic constituent of everything. It is air that produces water and soil upon condensation, and produces fire upon expansion. On the other hand, **Empidocles** said that everything around us is made of four constituents: earth, water, air, and fire. And then there is the atomic theory of **Leucippus** and **Democritus** (first half of 5th century BC), which says that everything is made of minute particles, called atoms.

The Ionian period also saw great advancement of medical science in the hands of **Hippocrates**, who tried to free the medical science from the ancient superstitions and "magic cures." He stressed on meticulous observation of patients to learn the nature of the diseases. The code of conduct in medical ethics—the so-called *Hippocratic Oath*—is still in use today.

Another question concerned the structure of the universe. **Anaximander** thought that the Earth is at the centre of the universe, that the sky is a hemisphere surrounding the Earth, and that the stars revolve round the north star. According to **Anaximenes** (who thought that air is the basic constituent) the earth, the sun, and the moon float in a sea of air. He thought that the stars are hot bodies attached to the celestial hemisphere; they are not as bright as the sun because this hemisphere is placed at a far distance than the sun. The Pythagoreans imagined that the earth, the sun, the moon, and other celestial objects revolve round a central fire (this is *not* the sun). Not only that. Based on their belief that the number 10 is a perfect number, they argued that there must be 10 celestial objects. At that time nine objects were known: Earth, Sun, Moon, Mercury, Venus, Mars, Jupiter, Saturn, and the ce-




Left: Democritus of Abdera (460-370 BC), right: Pythagoras of Samos (572-497 BC)

lestial hemisphere containing the stars. So, to make up the number 10, they imagined that there is also a "Counter Earth" revolving around the central fire, which is not visible from the northern hemisphere.

Thus we see that in the Ionian period, people considered the natural questions that comes to one's mind, and tried to answer them. But in answering the questions, they resorted to speculation and personal realization. In most cases the answers they arrived at were wrong. But one noticeable feature was that the answers were wholly in terms of the material things we see around us, that is, their ideas were in content materialistic. Idealism as we know it was not yet born. Historians have attributed this aspect to the fact that, in this early phase of the Greek society, slavery was not yet so strongly entrenched to create a hard division between the doer and the thinker.

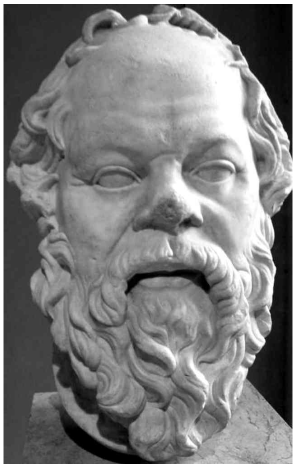
The Athenian Period

Towards the end of the Ionian period there was warfare with Persia and between the Greek states (called the Peloponnesian war) which suppressed many of the city states, but Athens stood up to the enemy under the leadership of the able statesman Pericles. As a result, Athens emerged as the Greek intellectual centre, and remained so over the period from 480 BC to 330 BC, culminating in the suppression of the city-states by Alexander.

In this period, in spite of the great advancements in the intellectual pursuits, we begin to see the effects of a society strongly based on slavery: the slaves who did all the work were not engaged in thinking, and the thinkers who came from the class of slave masters, had no connection with work, that is, the actual manipulation of natural objects. In this period the interests shifted from the explanation of the material world to that of the nature of man, his ideals, etc. Three great figures of this period are Socrates, Plato, and Aristotle.

In the city-state of Athens, a kind of democracy prevailed (albeit a democracy of the slave-owners) in which disputation and oratory skills had ever greater importance. In the words of J. D. Bernal, "The control of people by words became more rewarding than the control of things by work." In this situation **Socrates** (469-399 BC) developed and taught a method of argumentation in which, by asking a series of questions directed at the opponent's own knowledge, he would demonstrate that his opponent did not know what he was talking about. In essence, Socrates was introducing a method of logic in which great importance was attached to the rigorous definition of each term, which was to have great influence on the development of science in future.

In those times there was a tussle between the followers of democracy and those of monarchy. Socrates himself was not a supporter of democracy. In the middle of the 4th century BC, there was a war with Sparta, in which Athens was defeated. Then in 403 BC, there was a popular revolt that restored democracy. Socrates' death was a consequence of the fact that some of his disciples—young men of aristocratic



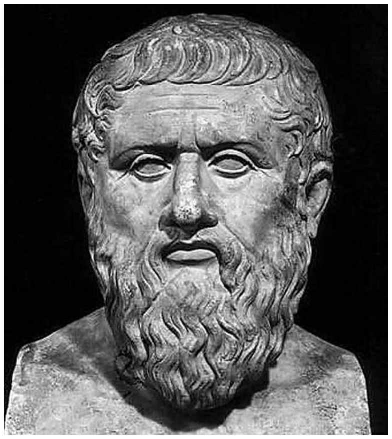
Bust of Socrates (469-399 BC)

families—went against Athens during the war with Sparta, due to which Socrates was accused of "corrupting the minds of young men".

Plato (427-347 BC), son of a wealthy aristocrat and a disciple of Socrates, was also a supporter of monarchy. In his youth, he dabbled in politics, but decided to devote himself to philosophy after his political ambitions were thwarted by the re-installation of democracy. He opposed the materialistic position of the Ionian philosophers like Democritus, but absorbed the mathematical mysticism of Pythagoras. He then went a step further to argue that the ideas taking shape in human mind are the perfect things; these are the actual reality. The *idea* of the 'circle' is actually the reality, and the circular shapes that we see in nature or can draw on a piece of paper are only imperfect approximations to this idea. He argued that since any beautiful thing has some imperfections, the idea of "beauty" is more powerful and more real than any beautiful thing. The philosophical trend he gave birth to is called *idealism*. It places idea in a higher position than matter, and holds that idea is primary and matter is secondary. It was only a small step from there for the later philosophers to declare that the material world is an illusion, and only ideas represent reality.

Plato then tried to speculate what should be the "ideal" things in every sphere of life and society. He used Pythagorean mathematics to create a peculiar kind of astronomy which tried to figure out how the motion of the heavenly bodies *should be* rather than how they really are. In politics he developed the concept of a "perfect State". According to Plato, the citizens of such a perfect state would be divided into four grades: the guardians, the philosophers, the soldiers, and the people—a division similar to the caste system in India (slaves did not come into any of these categories, because he did not consider them as citizens). He argued that these divisions are permanent because men are *created* in four constitutions—gold, silver, brass, and iron. He also imagined an "ideal" ruler, one from the category of the guardians, who would have no family life, no commitment other than that to the state. He would be a cultured person, highly educated in philosophy and mathematics, and should have a taste for music and the arts. Plato even tried to train Prince Dionysius of Syracuse in his ideal form, and failed (this boy could not stand the rigours of a training in mathematics, and did not want to remain a bachelor lifelong). He then returned to Athens, and created a school called the *Academy*, where he taught to a very select group of pupils. Over the gate was written "Let no one ignorant of mathematics enter here." The Academy survived more than a thousand years, and acted as the precursor of all modern universities and scientific societies.

Thus we see the birth of a mature form of idealism in the hands of Plato, expressed in such beautiful and persuasive language that it influenced generations of intelligent



Statue of Plato (427-347 BC)

people into philosophical idealism, utopian thoughts, and mysticism. As we shall see later, this trend blocked the advancement of scientific thought for a long time. In the realm of politics, his ideas regarding the affairs of the state were essentially to give a philosophical justification to a permanent rule of the aristocracy.

Aristotle (384-322 BC) was a disciple of Plato and later a rival who broke away from the Academy and started his own school—the *Lyceum*. He was truly an intellectual giant who had tremendous influence on human thought for more than 2000 years. He absorbed all the knowledge created till that time in different areas of human enquiry, and gave it a structured form as separate disciplines like physics, biology, humanities, etc., which continues to this day. He adopted the logic expounded by Socrates, and developed it into a system of thinking, called "formal logic".

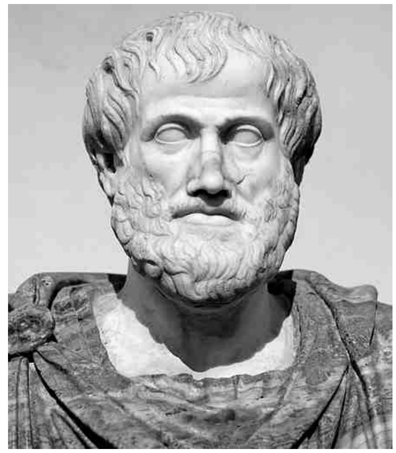
The theoretical structure he created in physics is worth mentioning. He adopted Empidocles' idea that water, air, fire, and earth constitute everything, and gave it a structured form as a system of "elements." To this he added "ether" as the substance of the heavens—an idea that survived until the early 20th century. According to him, all these elements have specific "nature". Why does water flow downwards? Because it is the *nature* of water to flow downwards. Likewise, it is the *nature* of fire to go upwards. According to Aristotle, everything has a natural place in the order of things, and tries to move towards that natural state when moved away from there.

Much of his ideas actually stem from common sense. He saw that the cart moves when pulled by the horse. So he theorized that "force produces motion." A logical corollary of this statement is that a greater force will produce a greater motion. That is what he said: "a heavier body will fall faster than a lighter body." This intuitive idea was so powerful that it prevented generations of scientists from checking it until Galileo Galilei did that in the fifteenth century.

In astronomy, he adopted the view that the Earth is at the centre of the solar system, around which moves the moon and the sun. Around that, there are transparent crystal spheres on which the planets are embedded. The planets move because these concentric crystal spheres move. Then there is the static, unchanging, dark hemisphere—the sky—on which the stars are embedded. That ends the universe, which, according to Aristotle, is finite.

But there is one field—biology—in which Aristotle did real scientific work. For a few years he lived close to the sea. When fishermen brought ashore various types of sea-creatures, he would collect them and would study their anatomy. In many cases he did dissection by his own hand (in this case he deviated from the slave-master attitude). In those days bee-keeping was an important activity, because honey was the only known sweetener. Aristotle made many important studies on such social insects. He even used his own resources to employ people to collect biological samples from distant lands. It is unfortunate that people after him did not continue this line of work, which was practically lost until the modern times. However, the limitations of his time show up at places in his biological studies also. For example, in the book "History of Animals" he said that human males have more teeth than females. Historians of science later commented that, had Aristotle bothered to actually count the teeth of one of his wives, this error would not have occurred. But the tone of the time was to arrive at an answer through personal realization, and Aristotle arrived at this conclusion based on the prevailing belief that women are inferior to men!

In Aristotle, we find the first in-depth treatment of the idea of causality. People before him had the notion that there must be a cause behind every event, but it was Aristotle who first gave it a theoretical form. He defined four types of causes behind every event: material cause, formal cause, efficient cause, and final cause. Consider a bronze sculpture, and ask what is the cause behind it? Aristotle says that the cause can be searched in four different ways. First, it is made of bronze. Hence the material, bronze, is a cause in the sense that the sculpture would be impossible if the bronze were not there. This is the material cause. Second, the sculpture has a form, and the sculptor had that *form* in mind when he worked on the bronze. This is the formal cause. Third, the sculptor is the external agency that acted in order to produce the sculpture. Hence the sculptor is also a cause—the efficient cause. The final cause is that for the sake of which a thing exists, or is done—including both purposeful and instrumental actions. The final cause, or *telos*, is the purpose, or end, that something is supposed to serve. This final cause had an obvious religious underpinning, and in the middle age the Church authorities made it their credo, thus making Aristotle their undisputed authority on every question.



Statue of Aristotle (384-322 BC)

Aristotle's contribution to the theory of logic is really momentous, and in this article we shall be able to give only a glimpse of his ideas. Picking up the thread left by Socrates, he developed a structured way of logical thinking that rested mainly on deduction, called *syllogism.* According to him, a deduction is speech in which, certain things having been supposed, something different from those supposed results of necessity. Each of the "things supposed" is a *premise* of the argument, and what "results of necessity" is the conclusion. Syllogisms are structures of sentences each of which can meaningfully be called true or false: "assertions" in Aristotle's terminology. According to Aristotle, every such sentence must have the same structure: it must contain a subject and a predicate and must either affirm or deny the predicate of the subject.

He then introduced the style of writing statements compactly in terms of algebraic variables, a, b, c, etc., which allows one to write a statement like "tigers are mammals" as "every b is a", where a represents the category of mammals and b represents tigers. He further compacted the notations by using letter symbols to represent the kind of statement one is making. For example, one would write the statement "every b is a" as Aab, where the first capital letter represents the Greek for "every" or "all", the second letter represents the predicate, and the third the subject. Using this, one can form abstract assertions like "every b is a" (abbreviated as Aab), "No b is a" (abbreviated as Eab), "Some b is a" (abbreviated as Iab) and "Not every b is a" (abbreviated as Oab). Then he outlines what are the logically correct deductions starting from a given premise (for example, $Aab \rightarrow Iba$: "every tiger is a mammal" implies "some mammals are tigers"). Thus, one would derive a series of such deductions, finally arriving at a conclusion quite different from the premise. He gives many more ways of such structured reasoning, which guided logical thinking for millennia. Much of Euclid's theorems in geometry follow this style of logical reasoning in their proof.

Following Socrates, he laid stress on proper definition of the things one is talking about. If you are talking about a tree, first define what a tree is. Take care to distinguish it from a sapling, a shrub, a bush, or a vine. For this purpose he proposed three principles of formal logic. First, the "law of identity" which says if you have defined an entity A, then A is A and nothing but A (abbreviated as $A = A$): A tree is a tree, and nothing but a tree. Second, the "law of negation" which says that no other thing is the same as A (abbreviated as $B \neq A$): A shrub is not a tree. Third, the "law of excluded middle" which says the nothing can be A and B at the same time: Nothing can be a tree and a shrub at the same time. For a long time scientific enquiry was

Euclid of Alexandria (325-265 BC)

guided by this style of reasoning, so long as scientists were studying "things as they are". It proved inadequate when scientists turned their attention to "things in motion and change". We shall come to this aspect later.

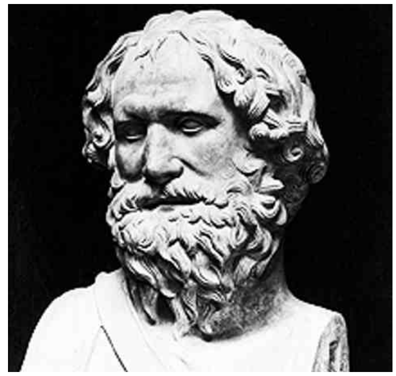
Even though Plato failed in his pursuit of grooming a prince, Aristotle succeeded. He taught the Macedonian prince Alexander (356-323 BC), who became the king of Macedon in 336 BC. In 334 BC he started his military campaign to spread the empire. He quickly subdued the city-states of Greece and invaded Persia. In a series of decisive battles, he defeated King Darius III of Persia, and spread his empire up to the river Indus. Then in 326 BC he invaded India. Even though he won battles, this terrain proved difficult for him, and he was forced to turn back at the demand of his exhausted troops. He died of disease in Babylon in 323 BC on the way back to Greece.

Before we move on to the Hellenistic period, we have to discuss the contribution of Theophrastus (373-288 BC), who studied in Plato's Academy and Aristotle's Lyceum, and became the head of the Lyceum after Aristotle's death. Under his leadership Lyceum became a famous centre of learning. He also made original contributions in botany and chemistry. Noticeable are the facts that in his writings he opposed some of Aristotle's doctrines including that of "final cause," and argued that fire cannot be an "element".

The Hellenistic period

After Alexander's death, the empire was divided among his generals. Seleucus occupied West Asia up to Punjab, while Egypt, Cyprus, Palestine and a part of today's Syria came to be ruled by Ptolemy. Civil war started for the occupation of Greece, and as a result the centre of intellectual activity shifted from mainland Greece to the other parts of the empire. This is called the Hellenistic period. The Egyptian coastal city of Alexandria, founded by Alexander the Great in 331 BC, became prominent in this period. The Alexandrian rulers, called the *Ptolemies*, patronized learning and scholarship, and founded a library which had the largest collection of books in the world of that time. Prominent figures of the Hellenistic period are Euclid, Archimedes, Aristarchus, Hipparchus, Claudius Ptolemy, and Galen.

Euclid (330-275 BC) worked in Alexandria during the reign of Ptolemy I (323-283 BC), and was the curator of the mathematics section of the library. He inherited a rich tradition of geometry, created and enriched by Thales, Anaxagoras, Pythagoras, Plato, etc. Euclid gave it a structured form, where the axioms were clearly stated, and theorems were proved based on Aristotelian deductive logic. His 13-volume treatise "Elements" is so comprehensive, that most of the theorems remained unchanged and form the backbone of school-level geometry even today.



Archimedes of Syracuse (287-212 BC)

Archimedes (287-212 BC) of Syracuse was another genius of that time. Though he is mostly known for the "Archimedes Principle" of hydrostatics, he was also a mathematician, an engineer, a physicist, and an inventor. He was educated at the library of Alexandria, and then returned to the island of Syracuse. His main interest was in geometry, in which he invented a method of obtaining the value of π, and developed the methods of measuring the volumes of various solid objects like sphere, pyramid, cylinder and cone. He overcame the limitations of the primitive number system of Greece (they did not use a place-value system and did not know the use of zero) to conceive large numbers, and used algebra to solve problems. Apart from discovering the "Archimedes Principle" which provided a theoretical basis for shipbuilding and maritime transport, he invented the "Archimedes screw" to pump water for irrigation, and gave a theoretical grounding to the theory of simple machines like levers and pulleys. Legend has it that he moved a whole ship using multiple pulleys in front of the ruler of Syracuse. Archimedes is said to have remarked of the lever: "Give me a place to stand on, and I will move the Earth."

At that time the Romans was at war with

Claudius Ptolemy of Alexandria (90-168 AD)

Syracuse, and the Roman ships laid siege of Syracuse a number of times. But each time Archimedes came up with ingenious methods to destroy the ships—some time with catapults that threw large boulders on the ships, some time using mirrors to concentrate sunlight to burn the ships. It appeared as if the Roman army was fighting against the mechanical inventions of a single man. But finally the siege of Syracuse in 212 BC succeeded in breaching the wall. Archimedes was killed by a Roman soldier while he was solving a geometrical problem.

Aristarchus of Samos (310-230 BC) was one of the greatest observational astronomers. He measured the distances to the sun and the moon, and estimated their diameters, and was the first to show that the moon is much smaller than the Earth, and the sun is much bigger. His observation that the sun is much bigger than the Earth made him doubt the prevalent belief that the sun revolved round the Earth, and he imagined a sun-centric picture of the solar system. But nobody at that time supported this idea.

About a century later **Hipparchus** of Nicaea (190-120 BC) further enriched this line of observational astronomy using the method of trigonometry. He is considered the founder of trigonometry, who compiled the first sine-table. He invented the astrolabe, an instrument used for measuring the position of celestial bodies. With its help, he compiled the first comprehensive star catalog, containing a record of 1008 stars. But he is most famous for his discovery of precession of the equinoxes in 127 BC. He measured the diameters of the moon and the sun to a greater accuracy than achieved by Aristarchus, through the use of trigonometry. Through his observations, he almost arrived at a heliocentric picture of the solar system, but abandoned it because his calculations showed that, if the sun were at the centre, the orbits of the planets would not be perfect circles, as was believed at that time due to the influence of Pythagoras and Aristotle.

We thus see that through the Greek period various philosophers and astronomers contributed to the conception about the nature of the universe, which reached its pinnacle through the publication of *Almagest* by **Claudius Ptolemy** (90-168 AD) of Alexandria. Ptolemy adopted the Aristotelian conception of an Earth-centric universe, but attempted to explain the detailed observations of Aristarchus and Hipparchus regarding the complex motion of the planets. In his conception, the Earth is at the centre of the universe, and the moon and the sun revolve around it. Beyond that revolve the planets, but not in circles. Their motions are on circles whose centres themselves move in circles around the Earth. The orbits of the planets, called epicycles, are thus given by circles moving over circles. At the far end of the solar system there is the dark canopy of the "sky" containing the fixed stars.

The famous fresco "School of Athens" by the renaissance painter Raphael, at the Vatican museums. Plato and Aristotle are shown as the central figures, Plato pointing to the heavens, and Aristotle pointing to the earth. Pythagoras in shown seated, to the left. Euclid is to the right of the picture, bending down to draw a geometrical figure on a slate. Claudius Ptolemy is standing behind him, holding the sphere of the Earth.

Conclusion

The Greek period spanning about 700 years from the time of Thales until the time of Ptolemy, defined the agenda of science—the basic questions to be probed. But the method of science was not developed at that time. As a result we see great thinkers engaging in speculation regarding the possible answers to these questions. Even though the method was speculative, in the initial Ionian phase the questions and their answers were by nature materialistic. But during the Athenian phase, the division in the society was more entrenched, the separation between the doer and the thinker more complete, and the thinkers had very little link with the material world. In this situation, even though the groundwork of logical reasoning was laid, the foundation of idealism was also laid—which retarded the advancement of science for many centuries. In the last phase we saw the beginnings of proper scientific pursuit through elaborate astronomical observations and advancement of mechanics, but for the most part these pursuits could not break away from the belief systems created in the Athenian period.

In the next phase we see the ascent of the Roman empire, the transition of the society from slavery to feudalism, and the dual rule of the king and the church over the population of Europe. That required a belief system, and for that they turned to Plato, Aristotle and Ptolemy. Thus the ideas of Aristotle became, in the hands of the Church, the mainstay of the Christian worldview. We shall come to that chapter of world history in the next part of this essay. □

(To continue in the next issue.)