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THE METHOD OF SCIENCE IN ASTRONOMY

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The Method of Science is concerned with the human search for knowledge of the natural world. Of this stimulating intellectual pursuit, and of the great strides accomplished therein over historical times, we have extant records, though often fragmentary, for perhaps over the last three millennia. Since the endless search and inquiry of truth and knowledge are basic to the deepest yearnings of the human mind, numerous distinguished thinkers of every age have attempted to analyse and identify the methods and processes by which knowledge of the natural world is acquired and augmented by repeated onslaughts of creative concepts and experiments. The method of science has drawn the greater interest of philosophers than that of scientists themselves, because to the philosopher the method of science provides clues to the general and basic problem of the theory of knowledge, its nature, limits and validity and in short to epistemology. In contrast, it is rarely of any practical benefit to the scientist in his own pursuit of scientific discovery and new knowledge.

Reflecting on the advances made over the last three thousand years in scientific thought and scientific knowledge, there is evident certain patterns, sequences and rationale which scientists seem to follow to make new discoveries. Two of the most glorious epochs of history, (not counting the 20th century), when human spirit burst forth and soared high into large scale creative excellence and thereby set high points and new standards in intellectual pursuits are those of the Greek philosophy of the 6th to the 3rd century B.C. and of the European Renaissance after two thousand years during 15th to 17th centuries A.D. Historians and philosophers of science attribute the two basic methods of scientific inquiry to those two epochs—the deductive method to Greek philosophy and the inductive method to the Renaissance.

Deductive and Inductive Methods

In the pure deductive method, one essentially begins with self evident premisses (first principles, axioms or hypotheses) which cannot be questioned nor called upon for a proof. They are assumed to be true because of their aesthetic appeal, beauty and simplicity—qualities which kindle and resonate with the deepest intuitive parts of human spirit. In other words, they can neither be demonstrated from phenomena nor they follow phenomena from arguments of induction. This of course is not to say that they are always correct as we will soon see. Given such premisses one proceeds by the use of logical or mathematical arguments to deduce consequences (theorems) and make predictions that pertain to the natural world of objects and phenomena. In a broad sense deduction proceeds from general to the specific, or from universal to the particular. At the same time it is important to remember that since the premiss is taken to be true, it only makes explicit whatever knowledge is implicit in the premiss. In geometry which has a pure form of deductive reasoning, the criterion for acceptance of an axiom or a system of axioms is that it should be free from contradictions, or in other words, the system should be consistent as a whole. The axioms are the works of our imagination. In science, the predictive success of the hypothesis is the only criterion for deciding its truth as is best illustrated in astronomy.

Induction, on the other hand, means reasoning in support of a general proposition of particular cases which fall under it. Aristotle called it 'a passage from individuals to universals' while in the nineteenth century A.D. John Stuart Mill called it as 'that operation of mind by which we infer that what we known to be ture in a particular case or cases, will be true in all cases which resemble the former in certain assignable respects'. These definitions tempt us to infer that induction and deduction are inverse operations of the mind.

In science, however, it is historically evident that new knowledge is not acquired by pure deductive or pure inductive methods, but rather by an alloy of the two with contributions from both but in varying fractions depending on diverse factors including the socio-religious milieu and the individual genius. Even the Greek period which is often considered to be synonymous of the peak of deductive genius, contains a considerable element of induction, and when scientific inquiry was attempted with deductive means divorced from experimentation and verification, the consequences were injurious to the cause of science as will be seen later. The inductive method which played a crucial role in the emergence of modern trends in scientific inquiry began with Copernicus, Kepler and Galileo and reached its pinnacle with Newton. It was believed by many leading philosophers of the time, and even upto the 19th century, that Newtonian mechanics is entirely perfect and it is in no need of improvement and cannot be superceded even in being explained by a still deeper or general theory. The superiority of inductive philosophies was thought to be in the fact that induction is self correcting. This was stated in explicit terms by C. S. Peirce as follows: 'the validity of an inductive argument consists in the fact that it pursues a method which if duly persisted in must in the very nature of things lead to a result indefinitely approaching to the truth in the long run'. Views on the methodology of science underwent newer changes with the dawn of the 20th century. The idea that science is, and ever will be, in a state of flux gained great approval with the epoch making genius of Einstein's theories of relativity followed by the developments in quantum mechanics, and in more recent decades, in High Energy Physics of the microscopic world and the astrophysics of the macroscopic world. This is well exemplified by Karl Popper's remark in *Logic of Scientific Discovery:* "I think we shall have to get accustomed to the idea that we must not look upon science as a body of knowledge but rather as a system of hypotheses; that is to say as a system of guesses or anticipations which in principle cannot be justified but with which we work as long as they stand up to tests and of which we are never justified in saying that we know that they are 'true' or 'more or less certain' or even 'probable'." Bertrand Russell also shares this view of Karl Popper; he says: "If we could prove that no other hypothesis was compatible with the observed facts we could arrive at certainty, but this is hardly ever possible".

It should not be interpreted from the foregoing that the method of science is just induction and deduction. It involves the complex working of the human intellect which often goes far outside of methods and definitions. Indeed its richness has been its diversity and one is often struck by the evidence from the history of science that all too often there is no regular procedure and no logical system of discovery. There are even instances where major discoveries have resulted from contradictions and inconsistencies. It will be my endeavour here to bring out the diversity, richness and sometimes baffling nature in the method of science as exemplified in astronomy through the advances in the study of Motion and Gravity from the time of Greek Science. Admittedly, the method of science is inextricably intertwined with the history of science. Hence to extract information on the method of science, a limited account of the history of science has also become unavoidable.

The Pre-Socratic Greek Science

The pre-Socratic period started with Thales in the Ionian colony of Miletus about 600 B.C. and ended with Democritus about 420 B.C. Political power was then in the hands of mercantile artistocracy who were actively engaged in promoting the rapid development of techniques on which their prosperity depended. Thales who was the first of the Milesian philosophers and a great traveller is thought to have brought to Ionia the knowledge of geometry from the Egyptians, of navigation by the stars from the Phoenicians and of astronomical tables from the Babylonians. But living amongst a pagan society he did an audacious thing for his time. He stripped all this knowledge and the cosmogonies of their respective myths, gods and religious inheritance. Instead of regarding stars as gods—which they were before him, and remained long after him to the time of Plato and others—Thales was first to treat them as natural objects. Ionian philosophy and tradition was thus a materialistic one devoid of gods of the Egyptians and Babylonians from whom they had borrowed the relevant science. We also see this trend in the thinking of Anaximander, also of Miletus, who thought of fish as a form of life that preceded land animals and that man, accordingly, had once been a fish; but as the dry land appeared, some fish adapted themselves to life on land, a view quite contrary to the creation story of the Babylonians and others of their time.

A word of general caution here. Are we tempted to infer from the above that Anaximander was able to anticipate, even in a crude way, the theory of evolution? If so we should be warned of the danger of attempting to read into the speculative views of such old thinkers more meaning from our own vantage position of the immense amount of accumulated knowledge during the intervening ages. At the same time we should be careful not to deny them the credit and recognition for their novel and independent manner of offering such explanations and interpretations in spite of the socio-religious environment in which they lived.

With Pythagoras, another stalwart of the Ionian period, originated the religious tradition of human thought on the nature of things. When he was about forty years of age (about 530 B.C.), the Persians conquered Ionia. He therefore fled from his native island of Samos to Croton where he founded a commercial city like his own. The Pythagorean community itself was a religious brotherhood for the practice of asceticism and the study of mathematics. The system found in mathematics a key to the riddle of the universe and an instrument for the purification of the soul. Of geometry Plutarch, a good Pythagorean says: "it draws us away from the sensible and the perishable to the intelligible and the eternal". And of numbers Philalaus another Pythagorean says: "consider the effects and nature of number according to the power that resides in the decade. It is great, all-powerful, all sufficing, the first principle and the guide in life of gods, heaven and men". For Pythagoreans, religion and mathematics were inseparable and their Mathematical Philosophy became a rival to the Ionian Natural Philosophy. They constructed matter out of numbers and a cosmos out of geometry—beautiful examples of symbolism. Naturally, the idea that heavenly bodies are divine led to their postulation that they are perfect spheres and have circular and uniform motion. It is also very interesting to note that in their universe fire was at the centre (not the earth or the sun) and the earth, moon, sun and the fixed stars moved around it. Pythagorean geometry was given a sound and formal shape by Euclid about 200 years later and hence the current reference to Euclidean geometry.

In the geometric view of the world, the Pythagoreans built their universe out of points with finite size. But when they discovered that the diagonal and the side of a square are incommensurable, i.e. the magnitude of the diagonal $\sqrt{2}$ is an irrational number, it followed that a line is infinitely divisible and hence points have no finite size. For the Pythagoreans who built their universe out of points and numbers, this was a shock and a crisis in science.

An account of Ionian science will not be complete without a mention of Democritus who lived about 420 B.C. The atomistic nature of matter proposed by Democritus is in some respects the culmination of the Ionian movement of inquiry into the nature of the universe and the working of nature by unseen bodies. His atoms had bulk but were indivisible and impenetrable; they were the building blocks of the natural world. This indeed is a beautiful example of rational speculation; or did it turn out to be 'rational' speculation? Finally, Democritus' statement: "nothing is created out of nothing" is a brilliant anticipation of the conservation of matter.

Brief mention may also be made of the school of medicine founded by Hippocrates (460-380 B.C.) which flourished essentially between the time of the Pythagorean school and the emergence of Socratic philosophy. They laid great emphasis in the careful observation and study of symptoms of the patient to infer the cause of pain and suffering. They were certainly against the method of some of the other schools of medicine who started with first principles—like heat, cold, moisture and dryness—for the origin and physiology of man and narrowed down the causes of diseases and death. An unknown physician of the Hippocratic school wrote. "For the sense perception coming first in experience and conveying to the intellect the things subjected to it, is clearly imaged and the intellect, receiving these things many times noting the occasion, the time and the manner stores them up in itself and remembers. Now I approve of theorising if it lays its foundation in incident and deduces its conclusions in accordance with phenomena". This is a clear example of the inductive method of inquiry adopted in medical science with tremendous success when all around man's thoughts were so seized with superstition and myths. Notwithstanding, much of the Hippocratic Corpus was in fact more philosophic, and these were mixed intimately with the genuinely inductive part.

To summarise, the Natural Philosophers of the pre-Socratic period, other than the Pythagoreans, offered essentially a materialistic explanation of the evolution of cosmos; they emphasised the ideal of positive science and endeavoured to demonstrate that man, through his conquest of techniques is the author of his own progress. In all this, the Ionian ruling class's dependence on technology for their continued prosperity, and victory over enemies, seemed to have played not a little part in providing them with the necessary intellectual slant and motivation.

The Athenian Science

We now come to Socrates (469-399 B.C.), the father of the Athenian School of philosophy. He was essentially a moralist and a philosopher who brought philosophy from heaven down to earth and diverted attention from physics and technology to ethics. What we know about him is essentially from the writings of Plato (427-367 B.C.) who attributed to Socrates the highest place for pure reason. Socrates discouraged research into nature and substituted a religious view which came down from Pythagoras. It may not be far wrong to say that he made no worthwhile contribution to science or the cause of science. As for Plato we have extant almost all his published work in the form of dialogues, though his oral instructions at the Academy have perished. From these we learn that he followed the general trend of the Pythagorean philosophy about the immortality of the individual soul; his reverence for geometry as the essence of his philosophy was demonstrated by a writing over the door of his Academy: "you cannot enter here unless you know geometry". Plato considered astronomy as well as accoustics as an impious study. In "Republic", he makes Socrates say: "you mean those gentlemen who tease and torture the strings and rack them on pegs of the instrument. . they too are in error like the astronomers". Thus, following Socrates, Plato also made no contribution to science and yet he advanced the study of logic more than any one else before his time. In the debate as to whether reason or senses is the true path to knowledge, Plato had come heavily in favour of reason; he claimed that sensation is not in itself knowledge.

In contrast to Socrates and Plato who were ardent proponents of pure reason and outright antagonists of science, Aristotle (384-322 B.C.) was both a philosopher and a scientist. Twenty years of his formative years spent at the Academy of Plato did not dim Aristotle's genius or independent thinking. In 348 B.C. when Plato died Aristotle complained that the Academy was turning philosophy into mathematics and left Athens for Ionia. He returned to Athens in 334 B.C. when he established his own school at the Lyceum. In Aristotle's teachings is found an attempt to synthesise Platonic idealism with a commitment to the Hippocratic positive science. In his treatise "On the Heavens", Aristotle said that the heaven is a sphere because a sphere is the perfect figure: it rotates in a circle because only circular motion having no beginning and no end is eternal—beautiful, elegant and aesthetically appealing concepts and would have been called "rational" too if subsequently proved correct. To these he added the geocentric nature of the universe as a first principle. From these he deduced that the apparently erratic motion of the planets (which Plato called the vagabonds) can be explained as due to circular movement on eight spheres for Saturn and Jupiter, and many more for others thus totalling forty seven for all the planets; in this the first sphere is that of the fixed stars. More than 400 years later, the Aristotelian concept of the geocentric universe was elaborated and systematised by Ptolemy (85-165 A.D.).

Another area in which Aristotle's contributions had a decisive impact of lasting influence is in developing logic into a science. It started with the problem of Being (Existence and Knowing). The Greeks saw that knowledge consists both of a knower (philosophy) and a thing to be known (science) and the instrument that relates the two is logic. In the Ideal Theory, Plato separated mind, i.e. philosophy (idea or form) from matter, i.e. science. For Plato the truth of a statement can be determined only with respect to a whole system of truths. In other words, what changes of things pertains to the changing world of senses, but the idea or form is permanent and is the only valid science of knowledge. It is thus clear, Platonic logic could not give knowledge of the natural world. Aristotle's doctrine on the other hand claimed matter and form to be two aspects of existence. To show this he developed the fourfold causes—the material cause ("that out of which a thing comes to be"), the formal cause (the patterns or formula of the thing in question), the efficient cause (the primary source of the change or coming to rest) and the final cause ("that for the sake of which a thing is done", the ultimate goal). There is a correspondence between the cause and the material change. To Aristotle geometry is true because it corresponds to the facts of the ordinary macroscopic level. The development of the application of this idea of four causes of change to unify mind and matter and the creation and development of a rigorous system of logic with the doctrines of induction, definition and deduction with all the forms of syllogism to the newly created demands to establish the working of the four causes is one of the greatest contributions of Aristotelian creative genius.

The history of Greek science also suggests that their thinking was considerably influenced by the socio-economic-political milieu in which they lived. Take for example the Ionian science. The fact that a class of merchants and manufacturers whose very strength in staying in political power was their command and control of techniques gave rise to a powerful inductive science and a boldness to do away with gods and myths. But then what about Pythagoras who also lived during the Ionian period? Really we do not understand. Plato and Aristotle lived in a society in which the master and slave system was firmly established and accepted as the right thing. The parallel to the social structure was well reflected in the philosophy of these giants too. In the Platonic government, Plato's philosopher-aristocrats who constitute a minority of the people are to rule the rest. The government is for the good of the people but it does not require their consent. In Plato's concept of soul and body, and mind and matter, one finds the same strand of relations as between the master and slave. Aristotle too believed in the master-slave society and its extension to the role of philosophy and science. He asserted that mathematics was first born in Egypt because of the leisure that the priestly class enjoyed though it was generally known that the reason is that geometry arose out of a need to survey the land which was frequently inundated by the flood waters of Nile. In his first book on Metaphysics, he wrote about philosophy as opposed to technique as follows: "For nearly all the requisites (of techniques), both of comfort and social refinement had been secured before the quest for this form of enlightenment (philosophy) began. So it is clear that we do not seek it for the sake of any ulterior application. Just as well call a free man who exists for his own ends and not those of another (slave), so it is with this which is the only free man's science: it alone of the sciences exists for its own sake". All this is suggestive that in the real life situation there is more to the methods followed by scientists than pure rational thinking alone. Science indeed is a very human enterprise.

From the foregoing it is clear that historically Greek philosophy is the beginning of science. Notwithstanding, nothing even remotely comparable to the Greek explosion of knowledge occurred for the next 1500 years. And for this we do not have any adequate explanation. It was in the later Middle Ages that certain interesting events that were to exert a decisive influence on the progress of science (and of religion) took place in Europe: the Crusades which gripped the involvement of Europe and Middle East were just about over; the whole of Aristotle's writings were recovered; the rise of the first universities at Bologna in Italy, Paris in France and Oxford in England came into being; and the cathedral and monastic schools of the catholic church flourished and reached a high point. The seeds of the European Renaissance and Reformation were sown. It was then the task of St. Thomas Aquinas (1225-1274 A.D.), a Dominican friar, to reconcile the Aristotelian and Christian ideas of God, and to absorb Aristotle into the Christian faith and tradition. In *Summa Theologica*, a work of lasting importance, St. Aquinas writes: "the principles of any science are either self evident or derived from what is known through a higher science. The principles of sacred doctrine are so derived, as we have said". Such was St. Aquinas' reverence for Aristotle that he referred to him as "the Philosopher" to the exclusion of all others.

Science During the Renaissance

Aristotle's philosophies and the instruments of inquiry took a firm hold of people's thoughts and beliefs until the time of the European Renaissance and Reformation during the 15th and 16th centuries when the method of induction was employed in a powerful way by men like Galileo and Kepler. But before inductive methods can be applied to astronomy, it was imperative that the false premisses of the geocentric universe and circular motion of heavenly bodies be given up; they acted as intellectual shackles and drags preventing new developments. The credit for breaking these two shackles that chained human thought for 18 centuries goes to Copernicus and Kepler respectively.

Nicholas Copernicus (1473-1543) was born eighteen years after the printing press by movable type was discovered. He was a catholic monk and a contemporary of Martin Luther (1483-1546) and Leonardo da Vinci (1452-1519). Until the time of Copernicus it was the prevailing unquestioned belief after Aristotle and Ptolemy that the earth is the centre of the universe and the sun, moon, planets and other celestial bodies revolve round the earth; this was in conformity with the anthropocentric belief of the catholic church that man is the pinnacle of creation and hence the centre of the universe. Ptolemy had systematised geocentric astronomy by introducing for the planets epicyclic motions which are in the form of circles whose centres themselves move around on certain other circles. Copernicus was intensely dissatisfied with this complex system and could not accept that nature worked in such a fashion. This sense of intense dissatisfaction gnawed in his mind for almost a whole life time until by a leap of thought, and an unusual boldness and independence in the face of the orthodox belief of his own Order and the Church, he put the sun at the centre of things and lo and behold all the astronomical observations seemed to fall into their places in a simple and beautiful way. We see in this intellectual pronouncement an audacity of mind matched by that of Thales in stripping the technology and cosmogony of his time of the role of gods. In the moment of joy Copernicus wrote: "And so we have found an amazing symmetry with this mathematical system of the universe and a certain tying together of the harmony of movement and of the size of the orbs such as can be found in no other way". Notice the terms "amazing symmetry" and "harmony" which seem to be the qualities that Copernicus was looking for. The book containing his discovery printed at the cost of a Cardinal and dedicated to the Pope was given to Copernicus on his death-bed in 1543. Notwithstanding, when the true nature of the contents of the book was recognised, the Church proscribed it. Though still imperfect in many ways, the Copernican model initiated a revolution in basic scientific thinking which was to reach its culmination almost 150 years later in the works of Newton. This contribution of Copernicus is a supreme example of a new horizon that can be opened only by giving up an universally accepted but false premiss or hypothesis, and the unimaginable dividends it brings forth. And without such a step there can be no progress, only a stalemate. And remember, it took 2000 years to say it and uphold it.

Another successful revolt against long established authoritarian dogma that took place simultaneously in Europe was spearheaded by Luther. It overthrew Papal supremacy now more than 1000 years old and brought about the Reformation and Protestantism. What Reformation was to Christian religion, the heliocentric theory of Copernicus was to science. Did they have anything to do with one another? We do not know for certain. But we do know that firstly, there had grown by that time a social and intellectual climate which had become bold enough to question established authority that was arbitrary and irrational. Secondly, the two revolutions occurring at the same time reinforced each other and had a refreshing effect on the freedom of thought of succeeding generations. Yet of Copernicus, Martin Luther is reported to have said: "The fool wants to overturn the whole science of astronomy". And as though in earnest reply to this charge, Copernicus wrote in the dedication of his book: "If there be some babblers who though ignorant of all mathematics take upon them to judge of these things and dare to blame and cavil at my work because of some passage of scripture which they have wrested to their own purpose, I regard them not and will not scruple to hold their judgment in contempt".

Though the concept of the geocentric universe was replaced by a heliocentric one by Copernicus, the second mental manacle of circular motion of heavenly bodies still ruled high. Three years after the death of Copernicus was born Tycho Brahe (1546-1601) a great experimentalist who devised new and accurate instruments like the quadrant and the sextant to become the first observational astronomer. His painstaking measurements were accurate and reliable but his theory poor. Being a pious and superstitious man, Brahe did not accept the Copernican system. And yet the experimental approach to scientific problems received a tremendous thrust with Brahe. It was however left to Johannes Kepler (1571-1630) to capitalise on the admirable measurements of Brahe by a method of induction to arrive at the three famous laws of planetary motion. Working with Brahe at Prague, Kepler had access to his extensive experimental data. Kepler found after numerous and painstaking calculations that within the framework of the Copernican system and circular planetary orbits, he could not explain the careful and precise measurements of Tycho Brahe. After incredible labour and innumerable wrong guesses, he gave up circles and ovals. Then in line with the pioneering spirit of the times he tried the ellipse. And the ellipse did work and all of Brahe's data clicked into their place. By a method of induction he generalised planetary motions. But notice that Kepler's laws are essentially facts that describe planetary motions; but they do not offer any explanation for their cause. The third book written by Kepler embodying a clear exposition of the Copernican theory was also proscribed by the Church. It is indeed sad to note that both these pioneers died of misfortunes and penury.

A lesson that we learn from the life's work of Copernicus and Kepler is that what appeals to men, even of the calibre of Aristotle, as aesthetically perfect and natural, does not always turn out to be the mode in which nature operates.

We now come to Galileo Galilei (1564-1642) an experimental scientist par excellence, and a devout catholic all through life. He was born the year that Michael Angelo and John Calvin died. Renaissance and Reformation were in full swing. And yet Galileo's task was not any easier either with the Church or with the intellectuals of his time. This is because men's thoughts had solidified with the philosophies and writings of yonder men, and human spirit was yet under the bondage of tradition and superstition. Of the numerous scientific contributions that Galileo made, the one that was of monumental importance, and which was to influence successive generations of scientists, was the Laws of Motion of falling objects which began with his legendary experiments with falling objects of different weights from the Leaning Tower of Pisa before the assembled members of the university. This experiment proved that two objects of very different weight fell to the ground together. But Aristotle had written that objects fell at different rates depending on their weight and therefore other intellectuals as well as the Church refused to accept the results of the experiments to which they themselves were witnesses. Galileo followed these experiments with the invention of the telescope and stunned the world with the discovery of a whole host of astronomical objects and phenomena; mountains and craters on the moon; the moons of Jupiter; the waxing and waning of Venus; the planet Saturn; spots on the Sun; and many others each contradicting the immutability, perfection and permanence of the heavens as believed for millenia. It is said that when invited by Galileo to view the sunspots through the telescope, the philosophers refused since they claimed that the sun cannot have spots on "rationalistic" grounds. (But let us not in India take pride and hold them to ridicule for we too in the 20th century acted in a somewhat like manner—scientists and common people—refusing to view the total solar eclipse of Feb. 16, 1980). Another extremely interesting fact is that Galileo, though born 21 years after the death of Copernicus, yet attempted his early understanding of the heavens within the framework of the Ptolemaic geocentric system. It was only after his discoveries with the telescope that he abandoned it in favour of the Copernican heliocentric scheme. The persecution of Galileo by the Church began soon after. In 1615 he was called to Rome to explain his views to the Pope and the College of Cardinals. He was summoned again in 1633 to Rome, this time for an inquisition, and after four months of agonising trial forced to recant which he did. In prison, in his seventies, he formulated the three axioms regarding the motion of objects and laid the foundation of mechanics—one of the outstanding contributions of Galileo's life's work. He went blind in 1637 and died in 1642. What an inglorious end to such a creative genius.

Galileo's monumental achievements in astronomy stemmed primarily from an inductive approach and it is evident that the conflict between him and the inquisition is that between the spirit of induction and that of deduction. In a sense Galileo may be considered as the first of the modern scientists because even men like Brahe and

Kepler had great faith in astrology and could only be called medieval. Galileo looking into the sky with his telescope stripped the heavens of their age-old mystery and divinity. It is no wonder that the emergence of the experimental method and the consequent, but unexpected, discoveries in astronomy should bring forth a great proponent of inductive philosophy like Francis Bacon (1561-1626). He led a bitter and relentless reaction against the deductive philosophy of Aristotle of whom he wrote: "He did not consult experience as he should have done, but having first determined the question according to his will, he then resorted to experience and led her about like a captive in a procession". He wrote extensively on the inductive approach in science, and influenced considerably many succeeding generations of scientists.

Newtonian Science

The stage was thus set for Isaac Newton (1642-1727) who was born in England the year that Galileo died. A right man at the right time. He was a colossus of his, and all time. To Newton goes the credit of many fundamental discoveries in physics and mathematics, each one more than equivalent to the life's work of a Nobel Laureate of today. These include the Binomial Theorem, Infinite Series and Differential Calculus in mathematics, and the Spectral Nature of Light, Refraction of Light, the first Reflecting Telescope, the Laws of Motion and the Law of Gravitation in physics. There was a great change coming over the mental outlook and value system of the people of England of those days. There was an increased awareness on the part of even politicians and others about scientific matters and the role of scientists in discovering new knowledge about the physical universe. It is perhaps for this reason that, contrary to the persecution and dishonour that were heaped on men like Copernicus, Brahe, Kepler and Galileo in the mainland, Newton was honoured by his country; and when he died at the ripe age of 85 he was buried at the Westminster Abbey, six peers bearing the pall. The two centuries following Newton now go by the name of Newtonian Era.

Among all his discoveries, the Law of Gravitation elaborated in his book *Principia* was the supreme one. Kepler's laws of planetary motion represent only an attractive and elegant codification of observed effects—they are essentially facts. But Newton's law of gravitation gave the explanation to the effect. This he achieved by introducing a beautiful but simple conceptual idea that all material objects—big and small—attract one another in a simple but specific and quantitative manner. He demonstrated through this concept that the same physical law which makes apples fall to the ground on earth also governs completely the motion of heavenly bodies. In essence he universalised a physical law for the first time. Simply stated, Newton's law of gravitation says that every material body (mass m_1) attracts every other body (mass m_2) with a force (F) proportional to the product of the two masses ($m_1 \times m_2$) and to the inverse of the square of the distance between the two ($1/r^2$); that is to say the force depends on the quantity $\frac{m_1 \times m_2}{r^2}$. Newton postulated that this force of attraction is due to the property of gravitation attributed to all material bodies in the universe independent of any other property or consideration. In other words, it is a constant quantity G, an universal constant applicable to all nature. It enabled Newton to write that the force of attraction between the two bodies $F = G \times \frac{m_1 \times m_2}{r^2}$. This simple equation was able to describe fully and quantitatively all existing observations of the heavenly bodies. They include the orbital motion of the moon in the gravitational field of the earth, and also equally well a number of very small effects, or perturbations, on the moon due to the gravity of the far away sun and the still weaker gravitational effects due to other planets. It also explained the ocean tides, the precession of the equinoxes, and permitted the estimation of the masses of the sun and moon. In fact the universe seemed more like a predictable mechanical system in which the law of gravitation played the key role. On these ideas are built Newtonian mechanics and Newtonian relativity which were to have preeminence in physics and our understanding of the universe for over two centuries until Einstein appeared on the scene.

Newton himself vehemently disputed the validity of hypothesisation in science and claimed that his method is one of inductive philosophy. He wrote in *Principia:* "As in mathematics so in natural philosophy the investigations of different things by the Method of Analysis ought ever to precede the Method of Composition. This analysis consists in making experiments and observations and in drawing general conclusions from them by induction and admitting of no objections against the conclusions but such as are taken from experiments or other certain truths. For hypotheses are not to be regarded in experimental philosophy... By this way of analysis we may proceed from compounds to ingredients and from motions to the forces producing them; and in general from effects to their causes and from particular causes to more general ones till the argument ends in the most general. This is the method of analysis". And yet when we examine Newton's method carefully they appear as typical of an inducto-deductive approach. He made use of a vast collection of earlier observational data and analysis, made his own experiments and in trying to determine the cause of the motions of the heavenly bodies brought in a completely new conceptual idea that all material objects attract one another. The rest followed by a deductive procedure from the generalised law to discrete observations and predictions. Kepler's three laws of motion simply emerged as corollaries. We are tempted to ask why the world had to wait till Newton for proposing such a simple and elegant idea. There is perhaps no easy answer to this question. But it seems probable that among other factors the advances in experimental observations and even the social milieu to which the scientist belongs may give the right intellectual slant to make that leap of thought. There are also those who think that Biblical beliefs and the emergence of Reformation ignited by Martin Luther through his rejection of Papal authority, have contributed critically to the flowering of science during the 16th and 17th centuries in Europe and not in any other region of the globe without claiming any extra advantage or superiority for the Europeans. The important religious world views that provided this favourable climate for the scientific advances are thought to be: God is sovereign over all nature, and only God is divine, not even the sun, moon or stars; the created universe is like a machine obeying implicitly the design of the Creator; God is also Lord of history i.e. of experience and phenomena and hence experience has ascendency over reason; manual trades and works have religious sanction and hence human dignity; man has power over nature; man is emboldened to question authority with the rejection of the infallibility of Papal office by the Protestants; and so on. How much truth there is in this may be a debatable issue, but some of them seem quite pursuasive indeed.

There is yet another aspect which deserves emphasis. Set in the right perspective, a crucial element in this scientific revolution is the release of human mind from the bondage of age-old traditions, superstitions, myths, erroneous first principles and the contempt for experimental and inductive methods. The result is that the discoveries and advances made from Copernicus to Newton made null and void the entire scientific edifice that was built from the time of Greeks to the Middle Ages. In contrast even during the modern age of scientific explosion, the works of men like Planck, Einstein, Bohr and Chandrasekhar have not invalidated or disproved Newtonian science, only improved upon it. A final point of interest is that all these men from Copernicus to Newton were deeply religious and it does not seem to have made any difference to their scientific creativity.

Some of the leading methodologists of the 19th century like John Herschel and John Stuart Mills were of the view that Newton's mechanics is perfect and cannot be superseded by a more general theory. And yet we now know that though Newton's scientific contributions constitute a mighty leap forward in scientific knowledge, it was not the end of the story. Let us pick up one connecting thread between Newton and Einstein of interest to the present subject and illustrate the progress of the scientific method. Newton's historic achievements provided two very different descriptions for the mass of an object. We have already seen that while attempting to account for Kepler's laws of planetary motion, he was led to the Law of Gravitation according to which the gravitational force is proportional to the masses of the attracting objects, larger the mass greater the gravitational force. This is the gravitational mass of the body. To Newton also goes the credit of discovering the three Laws of Motion. According to them a body at rest offers resistance to being moved. It has an intrinsic "inertia" which requires that if it has to be moved from rest and accelerated to a final velocity, an external force has to act on it. (Acceleration a is defined as the rate of change of velocity). Newton's second law of motion states that the externally impressed force needed to cause an acceleration of a metres per second per second is proportional to a quantity m of the body ($F=m \times a$). This m is called the inertial mass. But the surprise was that the gravitational mass was identical to the inertial mass, a fact which puzzled Newton not a little though he had no explanation to offer. This intriguing but fundamental question, why the gravitational and inertial masses of bodies are always equal remained with the world without solution for about two long centuries until Einstein came on the scene, *Einstein's Theory of General Relativity and Geometry*

The success story of Albert Einstein (1879-1955) is well known. The eighteenth and nineteenth centuries had already witnessed an all round progress in mathematics, geometry, astronomy, physics and philosophy of science. The giants of these centuries include Coulomb, Euler, D'Alembert, Legrange, Laplace, Gauss, Riemann, Herschel, Faraday, Maxwell, Boltzmann and Mach. Then came Einstein with the right conceptual ideas and in a duration essentially of a decade, 1905-1915, revolutionised science and scientific method by his epoch making discoveries in Brownian Motion, Photoelectric Effect, Special Relativity, Equivalence of mass and energy through the famous equation $E=mc^2$, and his crowning glory, the General Relativity which he described as "the happiest thought of my life".

In 1905, while attempting to understand the motion of objects and systems moving with constant (or uniform) velocity, Einstein hypothesised for no compelling reason that firstly, such motions are always relative and that there is no absolute or preferred space or frame of reference; and secondly, there is an upper limit to the velocity above which no object or radiation can move and that this limiting speed is the velocity of light. The introduction of these two bold and conceptual ideas which run contrary to the very foundations of Newtonian mechanics led to the prediction of numerous consequences such as the equivalence of mass and energy ($E=mc^2$) and the dependence of the attributes of mass and time on velocity for objects moving at speeds approaching close to that of light. It enabled a level of generalisation in which the whole of Newton's laws of motion became an approximation of Einstein's equations of Special Relativity in situations of everyday experience where the velocities are much much smaller than that of light. The degree of conceptual novelty involved in the Special Relativity may be gauged from the fact that even distinguished scientists of the time such as Michelson, Lorentz and Poincare, were hostile to the idea. The fact that it took many decades for these predictions to be verified in the laboratory with fast moving atomic particles speaks enough for the power of Einsteins deductive method.

The deductive method of scientific discovery was taken to a supreme height by Einstein in his theory of General Relativity. As the name itself implies it concerns a still higher level of generalisation of relativity. In Special Relativity, Einstein had brought together uniform speed, space and time in the framework of flat space-time geometry. In other words it means that lines in this flat world are infinite in length and they go on for ever and ever. In General Relativity, through a grand flight of creative and intuitive thought unsurpassed for their simplicity, aesthetic appeal and beauty, Einstein unified space, time and matter. The deductive and predictive capability of this theory was therefore tremendous. Einstein achieved this essentially by doing away with flat geometry and bringing in certain abstract ideas of a new and sophisticated geometry invented by Gauss and developed by his student Riemann about six decades earlier. Until then Riemann geometry remained a mathematical abstraction but in Einstein it received its supreme application. In the framework of

Riemann geometry space-time is flat no more but curved. When Einstein through a leap of speculation and hypothesisation—qualities abhorred by Newton—used Riemann geometry to include space, time, matter and energy, the peak of his deductive genius was achieved. Quite importantly, the Riemann curvature of space-time became equivalent to the presence of matter. And the dual role of mass being simultaneously the source of inertia and gravitation became a property of Riemann geometry. Automatically in the special case of a world without matter, space-time geometry became flat and we get Special Relativity. How beautiful! The reason why Special Relativity is almost implicitly obeyed in the case of sub-atomic particles moving with velocities approaching that of light is that, compared to other forces of nature, gravitation plays here a negligible role which is to say that we are dealing with flat space-time geometry. The universal gravitational constant G of Newton was nothing more than the constant of proportionality in Einstein's famous equation that holds the essence of General Relativity. Thus we can say that the Theory of General Relativity is also the Theory of Gravity.

In General Relativity, space-time geometry which simultaneously describes space-time relationships between events and gravitational field, is related to the distribution of matter in the entire universe via Einstein's equations. These equations have many solutions and represent all possible space-time geometries i.e. different kinds of universes. Thus for the first time, cosmology which was until then in the realm of philosophy came within the description of physics. But which solution of Einstein's equations describes our universe? This is one of the outstanding problems of present day astronomy and cosmology that has become a tantalising one. This is so because of the very nature of the problem and the difficulty of subjecting different models arising out of different solutions to experimental verification. Einstein himself believed that the universe should be static—a first principle which turned out more of a prejudice. Therefore, when he discovered that his equations predicted a dynamic universe he added arbitrarily a term (cosmological constant) to make it a static one. Nevertheless, when soon after the expanding nature of the universe was established from astronomical observations, Einstein acknowledged the great blunder he had committed. Can it be said from this that the intrinsic "rationality" and "irrationality" of a first principle or axiom of high order of intuitive speculation are separated by the thinnest partition?

We have already stated that being a conceptual idea of unprecedented beauty, the predictive capability of Einstein's theory of General Relativity has been so far unsurpassed. Though it may be argued that from a practical point of view, and to the extent of our laboratory experience so far, these predictions involve only minor corrections to the predictions of Newton's laws of motion and of gravitation, yet there are some basic differences that we cannot ignore. Firstly and most importantly, Einstein's predictions have resulted from the use of a much purer conceptual idea and it has to do with geometry, the purest of deductive sciences; this has its special connotations. Secondly, even after six and a half decades of the most organised international storming on science to yield its secrets, and the exponential push and pull of science and technology hauling knowledge to newer and newer heights (such as Quantum Mechanics and the Uncertainty Principle), his predictions have stood the test of time to the accuracy of the latest measurements. Thirdly, the most fascinating and profound discoveries that are currently being made in astronomy and cosmology (such as Neutron Stars, Black Holes and Big Bang origin of the universe) are all within the framework of General Relativity.

Summary and Remarks

To summarise, there are broadly speaking two basic methods of science which come into play when new knowledge of the natural world is acquired. They are induction and deduction. By tracing the advances in human inquiry of Motion and Gravity as evident in astronomy over historical times, we have attempted to learn how the two methods manifest themselves. To begin with, the birth of natural philosophy in Ionia and Athens, some 2500 years ago, is a miracle in history. One is virtually at a loss to identify adequately well the factors conducive to it and to explain the Greek obsession with the desire for knowledge and how such a glorious and sudden flowering of a highly successful movement in search for knowledge confined to a few city states came about. We also do not understand how so many intellectual giants beginning with Thales and continuing upto Archimedes were packed into those few centuries amidst a strangling environment of superstition, myths and military adventurism. This phenomenon seems all the more inexplicable considering that unlike present day trends of highly organised intellectual pursuits, it was then entirely voluntary and nonremunerative. Finally, one wonders that if so much of their original writings survived for posterity in the primitive conditions prevalent those days, how much more should have been lost as is now well recognised. Let us remind ourselves that what we call philosophy today is essentially the Greek theory of knowledge, logic and metaphysics due to Plato and Aristotle; it gives us a measure of the stupendous nature of their gift to human knowledge.

The Ionian period lasting about two centuries saw the exaltation and the application of the inductive methods to yield highly successful utilitarian techniques. But this is not to say that deductive methods were ignored by all the thinkers of this time because we remember that Pythagoras, the originator of geometry and of the religious tradition too belonged to this time. And then equally suddenly deductive methods came into ascendancy as exemplified by the work of Plato and Aristotle. In this, geometry—the pure deductive philosophy—with its axioms and deduced theorems became the guiding method of acquiring all knowledge. To Plato, the purest of the deductive philosophers, the way to Truth, Beauty and Goodness was through geometry. Soon after them came Archimedes a great experimental scientist in the modern sense who used a blend of inducto-deductive method with supreme success.

The phenomenal advances in natural philosophy, and of knowledge in general, made by the Greeks endured for nearly 20 centuries. So we ask, why this long lull?

Have we lost for ever evidence of all flourishing science during the intervening period? We just don't know well enough. The next burst of human spirit took shape during the Renaissance and Reformation when the human mind in many ways freed itself of many of the bondages of centuries. In science the movement started as a violent reaction to the Atistotelian method. The pioneers paid dearly for their boldness in rejecting age-old tradition and superstition. But they cleared the way for the onset of modern science. Newton took full advantage of the extensive and accurate astronomical observations and their codification accumulated by the labours of many scientists like Kepler, Brahe and Galileo for almost two centuries, reinforced them with his discoveries in mathematics and built on them the edifice of Newtonian mechanics and relativity through a method of inducto-deduction. It was the wide ranging observational discoveries that provided a provocative hint for Newton's Theory which was to reign supreme for only two centuries. During this period there were many who believed that Newtonian physics is the last word on the subject and they claimed that it is completely rational. And then came Einstein on the scene and with one mighty swing of intellectual leap-frogging reached new heights of near-pure deductive methods. And the concept? Geometry. Einstein was thus a Platonic Astronomer and the method of science and geometry made a full circle from Plato to Einstein in about 2500 years. Of course, Einstein too was benefitted by the sum total of all the earlier work including the monumental advances of the 19th century in physics and mathematics. But Einstein's imaginative method was qualitatively many degrees higher in its subtelity, and its predictive capability was vastly superior to that of Newton because of the greater element of deductive philosophy in it. The fact that the basic axioms used by Einstein were not fully defined, and accepted without probing and enquiry, lent them tremendous power of generation and prediction. On the other hand an important difference between the deductive methods in science of Aristotle and Einstein is the latter's rational control of his conceptual ideas; there was no associated myths or blind beliefs in them.

One may venture to give some explanation to the waiting period of 2000 years between the Greek School and Newton (period I) in contrast to the mere 200 years between Newton and Einstein (period II). Of course there should have been a matrix of contributory factors to this. But let us try to guess some. Firstly, intellectual pursuits like inquiry into natural philosophy need adequate leisure time, a relaxed mind and the company of peers. In the uncertain economic and political climate and the blind socio-religious beliefs of the ancient days, the Greek Masters created schools with a favourable environment—an ivory tower—in a deliberate manner. These schools provided the necessary physical and intellectual shelter from the outside world and the opportunities for teaching students and dialogues with peers. It is perhaps the disappearance of such a system that was in one way responsible for the long gap in scientific activity. In contrast, during Period II the introduction of an increasing number and variety of machines facilitated more leisure for the people, and the establishment of numerous universities and institutions of higher learning provided the favourable academic climate; improved agricultural methods assured more regular supply of food. It is therefore no wonder that the second period of waiting for a new movement in science is just one tenth of the earlier one. Secondly, philosophic pursuits during Period I could neither promise material benefit nor any remuneration, whereas during Period II, scientific research was getting more organised and professionalised with state support thereby attracting more and more people to undertake scientific research. Thirdly, the enormous hold of deductive methods ingrained in religious beliefs during Period I acted as intellectual shackles preventing free thinking. When once these were broken during the period of Renaissance and Reformation progress in scientific research accelerated. Fourthly, the rapid advances of technology during the 18th and 19th centuries enabled experiments of greater accuracy and ingenuity to be made, thus providing an improved data base for greater flights of imagination.

A weighty question one would like to pose about future advances in this field is as follows. There is in science a hierarchy of theories, the higher one subsuming all the lower ones. The ascending order in generality and beauty from the foregoing example of Motion and Gravity comprises the laws of gravitation due to Galileo, Newton and Einstein in that order. Yet we have miles to reach the pinnacle of the pyramid. Einstein himself spent the last 30 years of his life in vain to develop a theory in which gravitational and electromagnetic fields will be unified. To achieve this ultimately, will it need another singular person with a high purity conceptual idea similar or higher than that of Riemannian geometry used by Einstein? Or with the exponential growth in science and technology combined with the forthcoming unique opportunities of space astronomies, there will be so much of accurate observational data collected and codified as rules, facts and figures that an inducto-deductive approach like the one Newton adopted will do the trick? Only time can tell.

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