Section A

History and Philosophy: Overview

How has one thought about science in times past and in various cultures? What are the more meaningful and rewarding ways to think about science today? Most definitions or characterizations of science fall into two categories:

The first says that science is the study of the natural world. If one includes applications of science, then immediately one is dealing with an un-natural world — one that reflects human activities, especially engineering and medicine. More difficult is the concept of the natural world. Surely investigating the blood circulation of a mouse is science, as is the study of its mating behavior. One then asks whether studying the circulatory system of a human is science. How about the study of his mating behavior? Of his art?

The second definition emphasizes procedure or technique. Does science involve the formulation of a theory and its subsequent testing? If so, how does one go about testing a theory in a historical science such as geology or biology? What distinguishes generalizations from hypotheses, from theories, from laws? Is there a scientific method(s); and if so, should it be applied to the study of human activities such as economics, governance, and art?

The following chapters address these questions: What is science? How have various cultures thought about science? What are contemporary perspectives on science and how have they evolved in recent centuries?

A1. Pre-Hellenic Science
A2. Hellenic Science
A3. Chinese Science
A4. Islamic Science
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A6. Inductive Logic, "Works," and Francis Bacon
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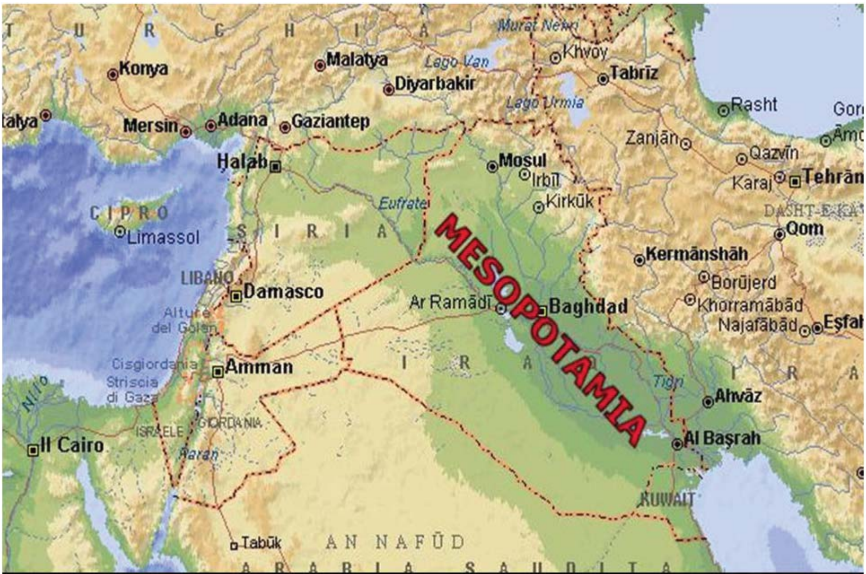
A1

Pre-Hellenic Science



A contemporary map of Iraq and the surrounding region showing Mesopotamia (literally, "between rivers").

As will be discussed in the next chapter, most historians, especially those in the West, appropriately turn to Greece to understand the origins of science, as well as many other intellectual endeavors. However, there are strong arguments for including engineering, informatics, medicine, and agriculture in the definition of science. If so, we should consider our first tools, garments, dwellings, and herbal remedies.

It requires reasonable talent to flake a stone and attach it to a handle to make an axe. It is hardly trivial to cure a hide and sew pieces together to make a cape or shoes or to bind branches and leaves to make a sturdy shelter. Chimpanzees use digging sticks to access termite nests. Other mammals and birds use tools and make complex nests and burrows. Macaws intuitively ingest clay, apparently to absorb toxins in some seeds that they eat. These skills are to some extent transmitted by imitation, but most are inherent. It seems reasonable to infer that some ability to do simple science is innate in our own species, as well as in others. There is overwhelming evidence that other complex behaviors are genetically encoded — so much for tabla rasa.

One can only speculate about the development of human language and the urges to do art and to do science. These intellectual abilities are probably inter-related. In any case, several fundamental achievements occurred independently several times in human evolution. These include the concepts of counting and adding, identification of stellar constellations, codification of medical practices, as well as the naming and grouping plants and animals. The assignment of names, stories, and powers to these constellations, animals, and practices reflects abstract thinking. These basic achievements of applied science occurred independently in Egypt, India, Mesopotamia, China, and Meso-America.

The earliest astronomer for whom we have records is Thales of Miletus (~600 B.C.). We are left to marvel as to why the Greeks extended these speculations and analyses to new levels of sophistication and abstraction. Did their achievements reflect unique environmental circumstances or the convergence of yet to be identified historical currents? Or were the circumstances that led to the appreciation of questioning purely stochastic? This is hardly a popular interpretation. However, the antecedents, if any, of Greek philosophy have yet to be established.

This chapter summarizes some of the early achievements of the Egyptians, Indians, Assyrians, and Babylonians — peoples of the Bronze Age in the Middle East. Subsequent chapters survey Chinese and Islamic science.

One refers to Egypt, after the unification of the upper and lower kingdoms about 3000 B.C., without exploring the subtleties of different dynasties. Lunar and solar calendars were merged; their calendar consisted of 12 months each of 30 days plus five special days committed to religious holidays. Sundials gave a precise definition of the solstices.

Much of their knowledge of anatomy came from mummifiers, who inserted a long hook through a nostril, broke the thin ethmoid and removed the brain. They removed viscera through an incision in the left groin. These procedures seemed not to have laid the foundation for further exploration of anatomy. Why were they not more curious?

The Ebers Papyrus (~1550 B.C.) listed some 877 "prescriptions" and noted a "… tumor against the god Xenus … do nothing there against." Homer (~700 B.C.) in the Odyssey noted that "… the Egyptians were skilled in medicine more than any other art." Herodotus (484–425) visited Egypt ~440 B.C. and wrote of their advanced medical practices. Pliny the Elder (23–79) praised their medicine. However, they failed to distinguish arteries from veins or nerves from tendons. The heart was assigned spirit and thought. Hippocrates, Herophilos, Erasistratus, and Galen studied at the temple to Amenhotep III across the Nile from Luxor. Peseshet (~2400 B.C.), mother of Akhethotep, was the first female doctor on record.

The Egyptians made potions or amulets with animal or plant parts that resembled afflicted regions — "*simila similibus*" (similar with similar), a concept not unknown to modern homeopathy. They distinguished phylactic, protection against demons, from theophoric procedures that invoked the help of a deity.

Herodotus in his *Histories* noted that circumcision was the norm and that the Egyptian military brought back uncircumcised phalli of Libyans as souvenirs. How might one evaluate the effectiveness, physiologically or psychologically, of their medicine? Or is effectiveness the right question?

The Edwin Smith papyrus (~1550 B.C.), Hearst papyrus (~1450 B.C.), and Berlin papyrus (~1200 B.C.) noted a range of foods and a sophisticated agriculture that reflected the importation of plants and animals from thousands of kilometers — "… milk, three kinds of beer, five kinds of wine, ten loaves, four of bread, ten of cakes, four meats, different cuts, joints, roast, spleen, limb, breast, quail, goose, pigeon, figs, ten other fruits, three kinds of corn, barley, spelt, five kinds of oil, and fresh plants …"

After the annual flood of the Nile, fields had to be re-surveyed; they made right angles using 3, 4, 5 triangles. We still marvel at their feats of civil engineering — pyramids, obelisks, the fabled light tower at Alexandria, and complex irrigation systems. Their ships could sail 90° to the wind. They made jars from molten glass. They made quality papyrus (paper) from reeds and developed hieroglyphs with phonetic symbols. Egyptians mastered a lot of engineering and agriculture. Many of these practices seemed to have remained unchanged from ~3400 B.C. until the Persian invasion of 525 B.C.

The people of the Indus valley, prior to 500 B.C., developed a calendar of 12 months, 30 days per month, with an intercalary month as needed about every sixth year. Their math incorporated zero and a base 10 number system; it included sine and cosine tabulations. Their metallurgy produced large cast iron pillars. They made stainless steel (wootz, with particles of Fe_3C) sword blades, later called Damascus steel in the West. Mercury and sulfur were used in metallurgy and as medicines. Several medical texts or vedas were compiled.

Just as Egypt developed beside the Nile and India on the banks of the Indus, so Mesopotamia developed between the Tigris and the Euphrates rivers in present day Iraq and southeast Turkey. The succession of peoples, languages, and rulers is complex. The important point is that by ~500 B.C. they had made significant advances. They developed a base 60 numeral system — hence our 60 minute hour, 24 hour day, and 360° circle. Al-Batani reckoned the precession of the earth's axis of rotation to be 54.5 arc-seconds per year; this compares well to the current value of 49.8 (see Chapter B3).

They were among the first to make quality bronze, cloth woven of wool and flax, and complex irrigation systems. Esagil-kin-apli of Borsippa wrote one of several *Diagnostic Handbooks* about 1050 B.C.

Egypt, India, Mesopotamia, and China (to be discussed in Chapter A3) all reached reasonable levels of sophistication with limited inter-communication. The details of their sciences varied. However, one can see that given a bit of political stability and economic self-sufficiency the pursuit of science and its applications seems inherent. These advances occurred before Thales (∼624–∼546 B.C., see Chapter A2) and a millennium of Greek leadership in inquiry. Islamic science (Chapter A4) built on the heritage of Egypt and Mesopotamia. One might then ponder why the Greeks tolerated all sorts of contentious speculations and why only in post-renaissance Europe did science proceed to higher levels of abstraction and sophistication.

A2

Hellenic Science

The School of Athens (1509).

The term “Hellenic” refers to both Greek language and Greek culture. Their civilization extended from Macedonia to southern Italy including Sicily, to Egypt, and to cities near the Mediterranean coast of present Turkey and Syria. Significant insights and innovations were made in mathematics, astronomy, physics, anatomy, and botany from 600 B.C. to 400 A.D. The empire of Alexander (356–323 B.C.) was fragmented soon after his death. It was not a unified kingdom with a single ruler or council and therein may have laid its intellectual vitality.

The Greeks were not the first to address abstract philosophies. However, what set them apart was their tolerance of, even pleasure in, disputation. This intellectual freedom was more limited in authoritarian or monarchical regimes. They posed questions, still relevant today, about the nature of knowledge.

This chapter provides a brief summary of these achievements. The impact of Greek mathematics, astronomy, and architecture on the Roman Empire, on the Islamic world, then on Western Europe are irrefutable. More problematic are their views on motion, the void, and atoms. One may question whether the "Great Chain of Being" of Aristotle or the anatomy of Galen advanced or hindered understanding of biology. This review of just their natural philosophy, or science, does not capture the full impact of their thinking.

Thales (∼624–∼546 B.C.) understood similar and right triangles; he calculated the height of a pyramid from the length of its shadow. Bertrand Russell opined that "Western Philosophy begins with Thales." Pythagoras (∼575–∼495 B.C.) is "…the father of numbers." He argued "… number is the ruler of forms and ideas and the cause of gods and demons." He gave the first proof of $a^2 + b^2 = c^2$; he realized that $2^{0.5}$ is irrational (Chapter B2). He analyzed vibrating strings and deduced that tones of a musical scale could be described as frequencies related as the ratio of whole numbers (Chapter D5). Euclid (∼300 B.C.) is "…the father of geometry." His *Elements* consists of 13 books and 36 propositions; it is the "…most important book of mathematics ever written." He also helped lay the foundations of number theory. Archimedes (∼287–∼212 B.C.) brought mathematical analysis to engineering. He analyzed the block and tackle as well as levers. "Give me a place to stand on, and I will move the Earth." He calculated the value of Λ by inner and outer polygons of 96 sides to be between $3 + 1/7$ (∼3.1429) and $3 + 10/71$ (3.1408). Hypatia (∼360–∼415 A.D.) was the first female mathematician of record.

Thales supposedly predicted a solar eclipse. Philolaus (∼480–∼385 B.C.), as cited by Copernicus, "… knew that the Earth revolves around a central fire." Plato (427–347 B.C.) wrote in *The Republic*: "We shall approach astronomy, as we do geometry, by way of problems, and ignore what's in the sky, if we intend to get a real grasp of astronomy." Aristarchus (∼287–∼212 B.C.) also argued a heliocentric model but could not detect the predicted parallax of distant stars. Eratosthenes (∼276–∼195 B.C.) made a map of the known (Mediterranean) world and developed a system of latitude and longitude. He calculated the circumference of the earth based on the angle of elevation of the sun at noon on the summer solstice as well as the tilt of the Earth's axis (23.4°, Chapter B3). Hipparchus is regarded as the greatest astronomer of antiquity; he completed the first comprehensive star catalog in the West. He developed spherical trigonometry and made accurate models of the motion of the sun and moon based on the concept of epicycles. He discovered the precession of the moon and estimated the eccentricity of the solar orbit. Proclus(412–485) made the last recorded astronomical observation of the Greeks in 475. It was a good millennium.

Thales argued that all matter is one, basically water. But how then could it exhibit so many properties? Anaximander (610–546 B.C.) adopted the concept of four elements (air, earth, water, and fire). Leucippus (~475 B.C.) explored the idea of atoms and empty spaces between them to permit motion. Parmenides (~515–~440 B.C.), in contrast, argued that the void is nothing; it offers no resistance, hence infinite speed and therefore movement is impossible. He also explored the duality of appearance and reality and concluded that truth cannot be known via sensory perception; only by pure reason, logos. All of this, long before Descartes (Chapter A7).

Democritus (~460–~370 B.C.) a student of Leucippus, elaborated on the nature of the atoma, "indivisible units," and argued that "…atoms and the void alone exist." However, he did not relate his atoms to air, earth, fire, and water. Aristotle (384–322 B.C.) attributed properties to air, wet and hot; to earth, dry and cold; to water, cold and wet; and to fire, hot and dry. He was aware of elements that we now know as sulfur (S), iron (Fe), copper (Cu), silver (Ag), tin (Sn), gold (Au), mercury (Hg), lead (Pb), and probably arsenic (As), antimony (Sb), bismuth (Bi), as well as numerous compounds: water, salt, acid, lye, alum, ochre, cinnabar, oil, pitch, steel, natron, wine, litharge, bronze, lime, vinegar. This seemingly inconsistent view — earth, air, fire, and water vs. elements — was not questioned.

Some anatomy and physiology can be inferred without experimentation. Hippocrates (~460–~370 B.C.), the "father of medicine," had no access to human dissections. He understood physiology in terms of the four humors — blood, black bile, yellow bile and phlegm — and rationalized diseases in terms of imbalances of these humors, or dyscrasia. He proposed standards of practice and distinguished between diagnosis, often to permit the family to plan, and treatment of which he had few. Aristotle (384–322 B.C.) distinguished aquatic mammals from fish. He noted stages of the development of the chick embryo, as well as of the mammal-like embryology of the hound shark, *Mustelus laevis*.

Herophilos (335–~280 B.C.) performed the first recorded dissections of humans, executed criminals, as cited by Galen. He distinguished motor from sensory nerves and assigned the site of intelligence to the brain. Erasistratus (304–~250 B.C.), a colleague of Herophilos in the school of anatomy in Alexandria, identified valves in the heart, recorded palpitations, and assigned its function as a pump. Galen (129–~208 A.D.) was a surgeon in the gladiator school of Pergamon; this provided him with "windows into the body." He also dissected various animals, including the macaque (barbary ape). His writings, with a few errors, became the reference point for copy or criticism by various Islamic and medieval anatomists. Herophilos and Erasistratus established a school of anatomy school in Alexandria where human dissections were permitted. They distinguished nerves from blood vessels and motor from sensory nerves.

Aristotle referred to observations of botany and zoology, as well as to experiments: "Salt water when it turns into vapor becomes sweet, and the vapor does not form salt water when it condenses again. This I know by experiment." He accepted various deities but distinguished logos from mythos. He suggested that plants have a vegetative soul and that animals have a sensitive soul. Humans are unique in having a spiritual soul. He sought a perfect representative of each species, the essence of typographic thinking, and the "Great Chain of Being" leading to humans at the pinnacle. One of the great challenges to biology of the scientific revolution was to refute many of these ideas and their overly simplistic interpretations. Theophrastus (370–~285 B.C.) was the guardian of Aristotle's children and succeeded him as leader of the peripatetic school where he argued against the "Great Chain of Being." He is credited as the first botanist to attempt some sort of classification — *Enquiry into Plants*, nine books, and *On the Causes of Plants*, six books. Pedanius Dioscorides (~40–~90 A.D.), a physician in Rome, wrote the first pharmacopeia, *De Materia Medica,* five volumes (Chapter C10).

In Raphael's *School of Athens*, Plato's hand points upward toward the heavens, Aristotle's down towards the Earth — idea and theory vs. observation and evidence. This image captures one of the great questions, still relevant today, addressed by the Greeks. Their achievements, from math through botany, comprise an impressive scientific legacy. More important, they posed abstract questions and sought general principles. Although the Greek worshipped many deities, they distinguished between mythos and logos and maintained that nature is ruled by laws (Chapters A5, A9, D3). Pythagorus argued that "... number is the ruler of forms and ideas and the cause of gods and demons." Many favored explanations that could be related to whole numbers or ideal solids. Were the stars fixed to the inner surface of a vast sphere? Could there exist anything beyond that, and how did this relate to infinity?

What of nature could be learned from observation? Would not experimentation "vex" the system and render it no longer natural? The attempts to make sense of the observed plants and animals begged one of the fundamental questions of biology: What is the appropriate or "natural" order of these organisms? Aristotle presented his "Great Chain of Being" as a hierarchy with insensate plants at the bottom, then soulless animals, topped by human beings. This led naturally enough to a ranking of humans, not for the first or the last time, with the home team inevitably at the top.

A3

China and Early Science

Zhang Qian travels to the West (Tang, 618–712).

The recorded history of China predates that of Greece and perhaps Egypt. China developed with minimal communication with the Mediterranean world. Many Chinese discoveries and applications of science predated the corresponding events in the West. The West had heard rumors about China long before Marco Polo traveled the silk routes. Francis Bacon referred to their great achievements — gunpowder, paper, printing, and the compass. Any simple enumeration losses detail and nuance; nonetheless, the overall impact is irrefutable. Between 500 and 1500 China was ahead of Islam and Europe in science.

This generalization suggests several inter-related questions. How or why did China make these inventions? Was their approach to science inherently different from that of the Greeks or of medieval Islam or Europe? These considerations lead to the Needham question: "Given the advances in science in China up to ~1600, why did science then stagnate?" This, in turn, begs the inverse Needham question: "Why did Europe enjoy such a fluorescence of creative energy during the renaissance and the subsequent scientific revolution?"

Joseph Needham (1900–1995), an embryologist in Cambridge, England, directed from 1942–1946 the Sino-British Science Co-operation Office in Chongqing, in central southern China well beyond the reach of the Japanese army (Winchester S. Bomb, book and compass: The fantastic story of the eccentric scientist who unlocked the mysteries of the Middle Kingdom, 2008). In addition to providing liaison and support to Chinese scientists, he traveled in western China and gathered information and artifacts related to the history of science. He subsequently founded the Needham Research Institute in Cambridge; it is still documenting the history of science in China. Many scholars have addressed the Needham question "Given the advances in science in China up to ~1600, why did science then stagnate?" Most interpretations include: "A general decline in the economy and vitality of the Ming (1368– ~1650) and Qing Dynasties (1644–1912) was reflected in diminished support for and interest in science." "The science of the preceding millennium was focused on application as opposed to abstractions; hence, could not advance." This discussion, then introduces the themes of Chapters A4 and A5 "Why did science suddenly flourish in the world of Islam and in Europe following the renaissance?"

The record of early scientific advances and technical applications is impressive. To the dismay of scholars, overviews of Chinese science often present a list of nominal accomplishments without exploring the details of the device or procedure. Such listings, superficial as they may be, do support several generalizations:

China developed productive agriculture by 6000 B.C. — wheat in the North, rice in the South — and an ensemble of related Mandarin dialects by ~3000 B.C., seemingly without knowledge of parallel developments in Egypt and Mesopotamia. China realized advances in engineering and medicine well before their counterparts in the Middle East or Europe. Its industrial might was impressively demonstrated by Qin Shi Huang (259–210 B.C.), first emperor of united China. He commanded the production of 8,000 terra cotta soldiers and 700 horses, discovered in 1970 near his mausoleum. How would one compare this, as a fraction of gross domestic product, with the Pyramid of Giza?

A few traders from the Middle East and India plied the silk route(s) to China before ~1000 A.D. Others traded with the Spice Islands. The existence of the Far East was rumored in medieval Europe. The Mongols, from Genghis Khan (1162–1227) to his grandson, Kublai Khan (1215–1294), reigned over most of China for a century. The accounts of Marco Polo (1254–1324) were widely circulated upon his return in 1295 from a 24 year sojourn. By 1549, Portuguese and Spanish missionaries were established in Nagasaki, Japan, and by 1582 in Macao, China.

Zheng-Ho of the Ming Dynasty (1368–1644) sent seven expeditions from the South China Sea, across the Persian Gulf, to the east coast of Africa (1405–1433). Among other artifacts, they brought back a giraffe. After the seventh, he banned further exploration, "been there, done that," and explored no more (until the last few decades, making up for lost time). In contrast to the Portuguese and Spanish, he did not send missionaries.

Although medieval citation indices are not so thorough or easily accessed, Francis Bacon (1561–1626) referred to the advanced state of Chinese civilization and specifically cited their inventions of "bombs, books, and compasses." The earliest reference to firecrackers is in 290 A.D., to a fire lance in 950, and to bombs launched from trebuchets in 1161. These were supposedly based on a black powder — charcoal, sulfur, and potassium nitrate. The *Diamond Sutra*, recovered from one of the Mangao Caves (Caves of a Thousand Buddhas) in 868 was block printed on paper made from wood pulp; it is a Chinese translation of a Sanskrit praise of Buddha. The use of naturally occurring magnetite (Fe_3O_4) rocks as compasses in navigation was recorded in 1116.

The earliest pottery has been dated to 10,000 B.C., seemingly before agriculture was established. Potsherds have been found in both the Yangzi and Yellow river basins, evoking comparison with the Nile, Tigris, Euphrates, and Indus. One succumbs to tabulating just a few of their most impressive early inventions:

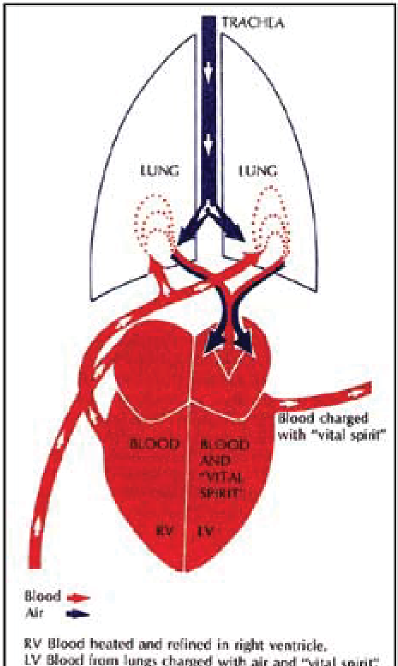
alcohol distillation	1500 B.C.
acupuncture	580
refraction of light	400
antimalarial, artemisinin	300
mercury distillation	300
diurnal rhythms and disease	200
circulation, arterial v. venous	200
goiter, treatment with iodine	100

The point of this discussion is not to compare each discovery with its counterpart in pre-Renaissance Europe. Most contemporary historians would agree with Bacon that overall the engineering in China was better than that in Europe. Further, it had been realized independently with little or no knowledge of the technical or of the philosophical achievements of the Mediterranean world.

These examples beg the fundamental question of whether and how society influences science and conversely how science affects society.

A4

Islamic Science



The minor circulation of the blood according to Ibn al-Nafis

Circulatory system.

During the century following the death of the prophet Muhammad in 632, Islam spread across North Africa into Spain and throughout the Middle East into North India. The apogee of that expansion might be considered to be the conquest of Istanbul in 1453 and the final demise of eastern half of the Roman Empire. That simple summary hardly captures the complexity of this movement; its ramifications are still being played out today. From the perspective of the history of science the important point is that Baghdad, Damascus, Cairo, Tehran, Cordoba, and other cities prospered and science flourished. These scholars, in contrast to their counterparts in China, were familiar with the writings of the Greeks and their translations to Arabic subsequently allowed medieval Europe its initial access to Greek scholarship.

Lord Dufferin in 1890 acknowledged: "It is to Mussulman science, to Mussulman art, and to Mussulman literature that Europe has been in a great measure indebted for its extrication from the darkness of the Middle Ages." C.H. Haskins wrote in 1927: "The broad fact remains that the Arabs of Spain were the principal source of the new learning for Western Europe." Arthur Glyn Leonard, 1909: "Do not we, who now consider ourselves on the topmost pinnacle ever reached by culture and civilization, recognize that, had it not been for the high culture, the civilization and intellectual, as the social splendors of the Arabs and soundness of their system, Europe would to this day have remained sunk in the darkness of ignorance?"

As is now well appreciated, the world of Islam had many achievements and insights beyond those of the Greeks. Yet, well before the expansion of European colonialism the science of Islam had run its course. As with China, one might ask the Needham question, *why*?

It is difficult to identify a single school or philosophical approach to science in Islam. There seemed to be an easy flow of men and ideas among these various centers — Bagdad, Damascus, Cairo, Tehran, Cordoba — and little conflict with, or regulation by, mosque or state. Summary descriptions of their various achievements speak to the strength of Islamic science, especially medicine, by 1300.

Al-Khawarizmi (780–850) was one of the founders of algebra; he employed a primitive form of logarithms. Al-Hasan b. al-Haitham (Alhazen) (965–1040) wrote works of mathematics and astronomy. He recorded eclipses, referred to the constituent colors of white light as seen in rainbows and invented a pinhole camera. He argued — contrary, to Plato, Euclid, and Ptolemy — that vision does not involve the emission of something from the eye. Al-Biruni (973–1050) suggested that the Earth rotates about its own axis. Shareef al-Idrisi (1100–1166) wrote of cartography and geography. Alhazen (Ibn al-Haytham) (965–1040) in his *Book of Optics* advocated experiments to test theories.

Abu Musa Jābir ibn Hayyān (∼721–∼815), known in the West as Geber, was a physician. He wrote a series of "books" or pamphlets, e.g. *Al-Zuhra* (*Book of Venus*) and *Kitab al-Ahjar* (*Book of Stones*) and the *Emerald Tablet* dealing with chemistry. He described the dissolution of gold in aqua regia (HCl and HNO_3) and reactions involving citric acid, acetic acid, tartaric acid, arsenic, antimony, and bismuth. As with many works, East and West, treating with alchemy, a bit of mystic symbolism (cf 119/11B5) seemed inherent to the protocols, hence the term "gibberish" (Chapter B5). In *Kitab al-Ahjar*, (*The Book of Stones*) he wrote "... alchemy is possible only by subjugating oneself to the will of Allah." He searched for al-iksir (elixir = make possible), i.e. the philosopher's stone. He argued the commonly held belief that the ratio of sulfur to mercury used in preparing the metal gave rise to different metals. Geber and contemporaries had yet to formulate a clear definition and theory of elements. He wrote “The first essential in chemistry is that you should perform practical work and conduct experiments, for he who performs not practical work nor makes experiments will never attain the least degree of mastery.” Alchemists in western Europe from ~1000 to ~1700 pursued similar goals. How and to what extent they communicated with their Muslim predecessors is not well documented (Chapter B5).

Avicenna (Abū Alī al-usayn ibn Abd Allāh ibn Sīnā (980–1037) wrote *The Canon of Medicine and The Book of Healing*, in which he discussed systematic experimentation, contagion, and quarantine, mediastinitis (mid-chest membrane inflammation) vs. pleurisy (membrane surrounding the lungs), tuberculosis, dermatitis, and sexually transmitted diseases. He believed the application of leeches to be more useful than cupping in “... letting of the blood from deeper parts of the body.” The use of zarnab, a mixture of alkaloids from *Taxus baccata*, for cardiac pain is the first recorded calcium channel blocker (Chapter C10). Several of his admonitions have a contemporary ring:

> The drug must be free from any extraneous accidental quality. The drug must be tested with two contrary types of diseases, because sometimes a drug cures one disease by its essential qualities and another by its accidental ones. The quality of the drug must correspond to the strength of the disease. For example, there are some drugs whose heat is less than the coldness of certain diseases, so that they would have no effect on them. The time of action must be observed, so that essence and accident are not confused. The effect of the drug must be seen to occur constantly or in many cases, for if this did not happen, it was an accidental effect. The experimentation must be done with the human body, for testing a drug on a lion or a horse might not prove anything about its effect on man.

His guidelines are reasonable, clear, and still relevant today; even though couched in the language of the time.

Numerous other authors wrote tracts on medicine: Ali ibn Sahl Rabban al-Tabari’s Firdous al-Hikmah (~860), *Paradise of Wisdom;* Muhammad ibn Zakarīya Rāzi (Rhazes) (865–925), *The*

Diseases of Children, in which he was critical of humorism; Ali ibn Abbas al-Majusi (~980), *Kitab Kamil as-sina'a at-tibbiyya*, *Complete Book of the Medical Art*.

Ishaq bin Ali al-Rahwi (854–931) al-Raha, in Syria, referred to medical peer review in *Ethics of the Physician*. Ishaq bin Ali Rahawi, Adab al-Tabib (in the 800s), *Conduct of Physicians*, called practitioners "guardians of souls and bodies." *Kitab al-Saydalah* in *The Book of Drugs* gave details of drugs and duties of the pharmacist.

Abu al-Qasim al-Zahrawi (Abulcasis) (~1000), *Kitab al-Tasrif* (30-volume *Book of Concessions*), described forceps for use in childbirth. Ibn al-Thahabi (~1000), in his alphabetical encyclopedia of medicine discussed diabetes mellitus, "… describing the abnormal appetite and the collapse of sexual functions and he documented the sweet taste of diabetic urine."

Ali ibn Abbas al-Majusi (1000), proved false the view that the "fetus swims out of womb" (per Hippocrates, Galen, Ptolemy), showing instead that it is aided by uterine contractions. Abu al-Qasim al-Zahrawi (1000), *Al-Tasrif*, wrote on obstetrics and mentioned forceps, catgut sutures, ligatures, surgical needles, scalpels, curettes, retractors, the surgical spoon, surgical hook, surgical rod, specula, and bone saw. Ferdowsi (1010), *Shahnameh* and al-Biruni *Al-Athar al-Baliyah*, described a caesarean delivery. Ibn al-Haytham (1021), in the *Book of Optics,* discussed the role of the retina in perception. Constantinus Africanus (~1087), in Salerno wrote a textbook of *Schola Medica Salernitana*. Avenzoar (1091–1161), in Andalusia, argued that scabies is caused by a parasite (the mite, *Sarcoptes scabiei*), not by humorism.

Ibn al-Nafis (1213–1288) had a broad understanding of anatomy: "The permeation of arteries into the cranium is well known not to be from the front ventricle." "The most important muscles of a human body total 529 …" He identified 10 cranial nerves and, in his *Book on Experimental Ophthalmology*, distinguished the muscles of eyeball from the optic nerve and noted that "… each nerve (of the eye) goes to the opposite side." He wrote that cognition, sensation, imagination, and locomotion emanate from the brain and described a harmony between religion and philosophy.

Muhammad ibn Zakarīya Rāzi (d. 925) wrote *Doubts on Galen*. He distinguished venous blood, which is dark, from arterial blood, which is light in color. He argued that the former came from the liver and the later from the heart and suggested that the "… blood pulse back and forth like tides." This view of circulation, analogous to respiration, was accepted until William Harvey published *De Motu Cordis* in 1628 (Chapter C3). Rāzi might be considered to be the first epidemiologist; he hung raw meat in various streets in Baghdad and sited his hospital in the area where the meat rotted least. Ibn al-Nafis practiced at the Medical College Hospital (Bimaristan al-Noori), Damascus, and at the Al-Nassri Hospital, 1236, and at Al-Mansouri Hospital, Cairo, as Chief of Physicians. He wrote the 80-volume *The Comprehensive Book on Medicine* in which he denied the existence of pores through the inter-ventricular septum. He wrote that blood from the right ventricle goes to the lungs; the lighter parts filter into the pulmonary vein, mix with air, and the blood mixed with air in the lung returns to the left ventricle, which receives nourishment from blood in vessels in its substance. He presented an accurate theory of pulsation. He elaborated: "The lungs are composed of parts, one of which is the bronchi; the second, the branches of the arteria venosa; and the third, the branches of the vena arteriosa, all of them connected by loose porous flesh."

> The primary function of contraction of the heart is to absorb the cool air and expel the wastes of the spirit and the warm air; however, the ventricle of the heart is wide. Moreover, when it expands it is not possible for it to absorb air until it is full, for that would then ruin the temperament of the spirit, its substance and texture, as well as the temperament of the heart. Thus, the heart is necessarily forced to complete its fill by absorbing the spirit. (Chapter C3)

Ibn al-Nafis noted that "… neither of the two semen has in it an active faculty to fashion"; they combine in the womb. Ibn al-Quff (1233–1286), a student of Ibn al-Nafis, described the formation of a foam stage in the first six to seven days, which in 13 to 16 days is gradually transformed into a clot and in 28 to 30 days into a small chunk of meat. In 38 to 40 days, the head appears separate from the shoulders and limbs. "The brain and heart followed by the liver are formed before other organs. The fetus takes its food from the mother in order to grow and to replenish what it discards or loses … There are three membranes covering and protecting the fetus, of which the first connects arteries and veins with those in the mother's womb through the umbilical cord. The veins pass food for the nourishment of the fetus, while the arteries transmit air. By the end of seven months, all organs are complete … After delivery the baby's umbilical cord is cut at a distance of four fingers breadth from the body, and is tied with fine, soft woolen twine. The area of the cut is covered with a filament moistened in olive oil over which a styptic to prevent bleeding is sprinkled … After delivery, the baby is nursed by his mother whose milk is the best. Then the midwife puts the baby to sleep in a darkened quiet room … Nursing the baby is performed two to three times daily. Before nursing, the mother's breast should be squeezed out two or three times to get rid of the milk near the nipple."

al-Quff continued: "Galen believes that each of the two semen has in it the active faculty to fashion and the passive faculty to be fashioned, however the active faculty is stronger in the male semen while passive in the female semen. The investigators amongst the falasifa (group of philosophers) believe that the male semen only has the active faculty, while the female only has the passive faculty … As for our opinion on this, and God knows best, neither of the two semen has in it an active faculty to fashion." "… once the male semen and female semen are brought together in the womb, the female semen quenches the hot fire of the male semen through its own cool and wet nature." (Chapter C5)

In the 1100s, two female physicians of the Banu Zuhr family served Almohad, ruler Abu Yusuf Ya'qub al-Mansur Şerafeddin Sabuncuoğlus. They dealt with not only clinical medicine but also fundamental questions of physiology and embryology. One may explore the sophistication of each of these practitioners. However, the general conclusion is solid: the practice of critical, informed medicine was widespread in the Islamic world. What then led to its stasis well before European conquests? This is a complex story, well beyond the scope of this book; however the Arab world was well aware of science in Europe. Darwin's *Origin* (Chapter C14) was translated to Arabic and had an impact on their scholarship and faith (Elshakry M. *Reading Darwin in Arabic, 1860–1950*).

A5

Christianity and Science

St. Thomas Equinas as depicted in *Wisdom Conquers Evil* (Santa Maria Sopra Minerva).

In contrast to the triumphant spread of Islam, the early centuries of Christianity were tenuous. The gospels of Mark, Matthew, Luke, and John, as well as of the early convert, Paul, gave different accounts of the life and teachings of Christ. Scores of heresies were debated and condemned. This complex web of interactions played out not only in the Roman province of Judea but throughout the Empire.

From the perspective of the development of science, there were two major themes: The early Church leaders, especially Paul (5–67 A.D.) and Augustine of Hippo (354–430), rightly argued that if the Church were to survive, it must establish a single doctrine and discipline its converts. This meant that philosophizing and speculation in matters both of faith and of science were not to be tolerated. Paul was unequivocal: "The more they called themselves philosophers, the more stupid they grew (Romans 1:21–22)." He declared war on the Greek rational tradition through his attacks on "… the wisdom of the wise …" and "… the empty logic of the philosophers."

Pope Gregory the Great warned those with a rational turn of mind that, by looking for cause and effect in the natural world, they were ignoring the cause of all things, the will of God. Science in the Greek world under the nominal suzerainty of the emperors in Rome and in Constantinople declined during the first four centuries A.D. This decline paralleled the rise in power and intolerance of the Church in both the western and eastern empires. Whether this correlation reflects causality remains a matter of debate.

The Draper–White thesis "… wedded a triumphalist view of science with a patronizing view of religion." "Grounded in faith, religion seemed bound to suffer when confronted by science, which was, of course, based on fact." — Gary Ferngren in *Science and Religion* (2002). These two books — *History of the Conflict between Religion and Science* (1874) by John William Draper, and *A History of the Warfare of Science with Theology in Christendom* (1896) by Andrew Dickson White — informed American views of the supposed conflict between religion and science.

E.R. Dodds in *The Greeks and the Irrational* (1951) wrote "… honest distinction between what is knowable and what is not appears again and again in fifth-century (B.C.) thought, and is surely one of its chief glories."

Colin Russell conceded "While it cannot be denied that isolated cases of real conflict have existed, as in the cases of Galileo and Darwin, recent historiography suggests that it would be wrong to extrapolate from these examples to the view that science and religion are necessarily hostile." Ferngren continued "… Christianity has often nurtured and encouraged scientific endeavor, while at other times the two have co-existed without either tension or attempts at harmonization. The story of science and Christianity in the Middle Ages is not a story of suppression nor one of its polar opposite, support and encouragement."

Charles Freeman in *The Closing of the Western Mind: The Rise of Faith and the Fall of Reason* (2005) argued that "… the central theme of this book (is that) … the Greek intellectual tradition was suppressed rather than simply faded away." He continued: "Paul … declared war on the Greek rational tradition through his attacks on "… the wisdom of the wise" and on "the empty logic of the philosophers." Paul "… formulated a meaning for Jesus' death and resurrection." "Unlike Jesus he insisted on a dramatic break with traditional culture, not only his own, but also that of the Greco-Roman world." He wrote "… that is anyone preaches a version of the Good News different from the one we have already preached to you, whether it be ourselves or an angel from heaven, he is to be condemned." "… an exploration of its (the crucifixion) meaning forms the core of his theology." "… sin is a heavy, albeit abstract, entity that burdens the human race."

Freeman continued: "Whereas in traditional Greco-Roman religion the public observation of rituals is primary, Paul presents something radically different proposing that the orientation of the inner person to God is essential. It is an idea that reached fruition in Augustine, who in his *Confessions*, talks of God actually being inside a person's intimate being and in a continual and often in Augustine's case, stormy relationship with him." "In the second Letter to the Thessalonians it is made clear that those who refuse to accept 'the Good News of our Lord Jesus Christ' will be punished for eternity (1:9)." "So for Paul it is not only the Law that has been superseded by the coming Christ, it is the concept of rational argument, the core of the Greek intellectual achievement itself." Paul preached "The more they (non-Christians) called themselves philosophers, the more stupid they grew (Romans 1:21–22)." "Gentile Christianity, through Paul, had declared war on the Greco-Roman world, its gods, its idols and its mores." "It was as a result of the urgent need to define its boundaries and beliefs that Christianity developed sophisticated notions and structures of authority."

Freeman concluded: "By fixing on a comprehensible symbol, the death and resurrection of Christ, by proclaiming the enormous and imminent rewards of Christian faith and the awful consequences of rejection of 'the cross of Christ', Paul had created a focus for community worship." "So here are the roots of the conflict between religion and science that still pervades debates on Christianity to this day."

The Roman emperor Diocletian in 302 allied himself with the ancient gods seemingly to minimize conflict:

> The immortal gods in their providence have so designed things that good and true principles have been established by the wisdom and the deliberation of eminent, wise and upright men. It is wrong to oppose these principles, or desert the ancient religion for some new one, for it is the height of criminality to try and revise doctrines that were settled once and for all by the ancients, and whose position is fixed and acknowledged.

Constantine defeated, then executed his rival in the East, Licinius, in 325; Licinius II was killed in 326. Constantine was supreme within the empire and, sitting on the "throne of gold," convened the bishops in the first council of Nicaea in 325. In all modesty he pronounced: "We have received from Divine Providence the supreme favor of being relieved from all error." Constantine was finally baptized in 337, weeks before his death. Thus began the jostling for state control of the Church and the Church's control of the state. The reverberations of this competition are still being played out in some countries today. Jesus became a god of war when about 375, Emperor Ambrose in *De Fide* proclaimed "... the army is led not by military eagles or the flight of birds but by your name, Lord Jesus, and Your Worship." This illustrates the fundamental significance of separation of church and state in many contemporary industrialized nations.

In 378, Goth refugees, fleeing the Huns, crossed the Danube. In the Battle of Adrianople, the Huns defeated Emperor Valens; 10,000 Roman troops were killed. Later, Theodosius, the local commander, ordered a massacre in 387 in retaliation for a rebellion in Thessaloniki. He asked for penance from Ambrose, recently baptized and installed as bishop, thereby establishing the precedent of the Church's forgiving and legitimizing political authority. Rome was sacked by the Visigoths in 410. This was the inflection point in the fall of the Western Empire and beginning of the Dark Ages.

Freeman continued: "Augustine believed that every other form of learning had to be subordinated to the scriptures ... secular knowledge, whether provided by mathematicians, scientists or philosophers, is said to be valid only insofar as it leads to an understanding of scripture." Even more extreme were "… John Chrysostom's exhortations to Christians to empty their minds of secular knowledge." "One important theme which has run though this book is the linking of belief in rational thought with a belief in free will."

"Thomas Aquinas (1225–1274) revived the Aristotelian approach to knowing things so successfully that he unwittingly laid the foundations of the scientific revolution that was to transform western thought." "In the year of his breakdown (1273) he was strongly criticized in Paris for his insistence on a natural underlying order of things" "It is not until the fourth and final book of the *Summa Contra Gentiles* that he introduces those Christian doctrines sustainable only by faith, which he includes the doctrine of the Trinity, the Incarnation and the creation of the world by God, *ex nihilo* … (The alternative view, held by both Aristotle and Plato (Chapter A2), which Aquinas accepted he could not disprove, was that matter had existed eternally alongside God)."

One is left to ponder whether Europe's millennium of darkness, from the sack of Rome in 410 to the siege of Vienna in 1529, should be attributed to the westward pressures of tribes from Asia, or to the anti-intellectual policies of the early church. As is often the case in historical analysis, one can document the occurrence of two events, e.g. the intolerance of early Christianity and the decline of science in Europe. The inference of causality is more tenuous, and yet …

A6

Inductive Logic, "Works," and Francis Bacon

Francis Bacon (1561–1626).

Francis Bacon was one of many who tried to free Western thinking from simplistic (mis)interpretations of Aristotle's works, or so-called scholasticism. He is credited with explicitly advocating what we now refer to as the inductive method. That is, one makes a series of objective observations, or experiments, and from them finds correlates. Many critics have noted the obvious: correlation does not prove causality. However, such associations underlie much of our learning and behavior. Later we will describe a more refined synthesis of inductive and deductive logic.

Fully as important, Bacon argued the societal value of "works" — what we might now call applied science — engineering and medicine. He also urged the government, King and parliament, to support scholars pursuing these works. Subsequently, many scientists, correctly or not, argued that they were following Bacon; he was cited by the founders of the *Royal Society of London for the Improvement of Natural Knowledge* in 1642. Whether his greatest influence lay in elaborating the inductive method or in his championing the value of works is problematic. The Scientific Revolution nominally occurred between 1600 and 1700. Bacon was one of its more influential figures even though he was not a scientist.

Francis Bacon (1561–1626) was the youngest of five sons of Sir Nicholas Bacon, Lord Keeper of the Great Seal for Elizabeth I. Francis and an older brother attended Trinity College, Cambridge from 1573–1576; he then traveled to Paris with his father who died in 1579 and left him only a small inheritance. Bacon attended Gray's Inn, residence in law, 1579, and became an outer barrister in 1582. He became a member of parliament in 1584 and urged the execution of Mary Queen of Scots. He was deeply involved in the intrigues of Elizabeth's reign and was an advisor to Elizabeth's one-time favorite, Robert Devereux, second Earl of Essex. Bacon subsequently investigated charges of treason against Essex and pressed for his execution in 1601.

Bacon was knighted by James I in 1603 and assumed the clerkship of the Star Chamber in 1608. He wrote the government report "The Virginia Colony" in 1609 and helped form the Newfoundland Colonization Co. in 1610. In 1618 he was charged with corruption (debt) by the Lord Chancellor and debarred in 1621.

Quite remarkably, Bacon had the breadth of interest and the energy to write, in several versions, the *Advancement of Learning* (1605), *De sapientia veterum* (*Wisdom of the Ancients*, 1609), *Novum organum* (1620), and the *New Atlantis* (1626). He criticized the pedantry of "post-Aristotelians" and described utopias: *Christianopolis*, Andreae (1619), *City of the Sun*, Campanella (1623). He argued that "… the sciences in their present state are useless for the discovery of works, so logic in its present state, especially obsession with 'Aristotelian' syllogisms, is useless for the discovery of sciences."

Bacon felt that the acquisition of knowledge must precede generalization and focused on the arrangements of things previously discovered, not methods of discovery. "… the sciences we now have are no more than elegant arrangements of things previously discovered, not methods of discovery or pointers to new results."

"… current logic is good for establishing and fixing errors (which are themselves based on common notions) rather than for inquiring into truth." He rejected "induction by enumeration" and advocated "rejections and exclusion" to trim conclusions down to one (as might be done by a lawyer or administrator). "The end of induction is the discovery of forms, the ways in which natural phenomena occur, the causes from which they proceed." Bacon had limited talent in mathematics and little sympathy for abstract theorizing.

He described an ideal college, "Solomon's House," remarkably similar to a modern research university devoted to applied and pure science. "The true and legitimate goal of the sciences is to endow human life with new discoveries and resources." "Just let man recover the right over nature which belongs to him by God's gift, and give it scope; right reason and sound religion will govern its use." These were appropriate Christian purposes. In his *The Essays: Of Atheism*, "… a little philosophy inclineth man's mind to atheism; but depth in philosophy bringeth men's minds about to religion."

These new ways of thinking first required rejection of:

- "Idols of the Tribe" (*idola tribus*), which are common to the race;
- "Idols of the Den" (*idola specus*), which are peculiar to the individual;
- "Idols of the Marketplace" (*idola fori*), coming from the misuse of language;
- "Idols of the Theatre" (*idola theatri*), which result from an abuse of authority.

Bacon was critical of contemporary (1600) interpretations of antiquity. "For the discovery of things is to be taken from the light of nature, not recovered from the shadows of antiquity." "… after Socrates had brought philosophy down from heaven to earth, moral philosophy grew still stronger, and turned men's minds away from natural philosophy." John Locke was influenced by Bacon and argued in his *Essay Concerning Human Understanding* (1690) that empiricism was the initial route to knowledge. For the next century, philosophers on the continent were more inclined to theoretical constructs than were their brethren in Britain.

Bacon was aware of the advanced state of science in China (Chapter A3). "Printing, gunpowder and the compass: These three have changed the whole face and state of things throughout the world; the first in literature, the second in warfare, the third in navigation; whence have followed innumerable changes, in so much that no empire, no sect, no star seems to have exerted greater power and influence in human affairs than these mechanical discoveries." Catching up was seen as a goal for Europe.

He understood that observation alone did not constitute inductive logic and offered a parable. Ants (as empiricists) "only collect and use"; spiders (rationalists) "make cobwebs of their own substance"; however, the bee "gathers … transforms and digests it by a power of its own."

Peter Dear, in *Revolutionizing the Sciences* (2004), paid him the highest compliment: "The modern world is much like the world envisaged by Francis Bacon."

A7

Deductive Logic, Maths, and René Descartes

René Descartes (1596–1650).

René Descartes, for whom the Cartesian coordinate system is named, is credited with describing and refining deductive logic, as summarized in his *Discourse on the Method* (1637). That is, given an initial set of assumptions and their logical development, the conclusion must be true if the assumptions were correct and the development was free of error. Although this assertion is generally accepted, it begs the question of how one chooses those initial assumptions. This deductive approach is often presented as the essence of how mathematics and physics is done. Yet, getting those initial assumptions and making legitimate approximations during the analysis can be extremely challenging and ultimately is informed by insights that need not be entirely logical.

Descartes championed dualism, i.e. the body works like a machine and obeys laws of physics; the mind does not. This is an extension of the arguments of Plato. He is remembered for the quotation "*Cogito ergo sum*" — "I think, therefore I am." His writings were generally endorsed by rationalists — Spinoza, Pascal, Leibniz — on the continent and criticized by empiricists — Hobbes, Locke, Berkeley, and Hume — in Britain.

Very roughly, this argument between rationalists and empiricists can be seen as an extension of alternate views of Plato and of Aristotle, captured in *The School of Athens* by Raphael, with Plato pointing to the heavens for mathematical purity and Aristotle pointing to the earth for observation.

René Descartes was born in La Haye en Tourain, near Richelieu, in 1596 and succumbed to the cold in Stockholm in 1650. He entered the Jesuit Collège, Royal Henry-Le-Grand, La Flèche in 1607 and received his baccalauréat and license in law in 1616 from the University of Poitier. His family was not wealthy; he had to work for his living. He served as secretary to Maurice of Nassau, leader of the United Provinces, Netherlands, in 1618 and was present at the siege of La Rochelle by Cardinal Richelieu in 1627. He visited or attended the universities of Franeker, 1629; Leiden, 1630; and Utrecht, 1635.

Descartes developed analytic geometry based on a coordinate system with three orthogonal axes, created exponential notation, and applied infinitesimal calculus to the tangent line problem. He helped wed the geometry of the Greeks to the algebra of the Hindus (Chapter B2).

From the law of refraction, ($n = \sin i/\sin r$; $n =$ index of refraction, $i =$ angle of incidence, $n =$ angle of refraction), he deduced the angular radius of a rainbow, 42°. He proposed the conservation of momentum. However, not all of his science was so analytical; he regarded the pineal gland as "the seat of the soul."

His *Discourse on the Method* (1637) was an explicit exposition of his deductive logic. Descartes maintained that the senses lack certainty; they can deceive. Human reason, including mathematics, is subject to error. He sought a fundamental set of principles that one can know to be true without any doubt. He wanted certainty rather than mere opinion; his ideas were to be "… accepted for their truth, not simply for their likelihood or even mere ingenuity." He sought to explore logic "… as if no one had written on these matters before." Descartes questioned what one actually senses: "Thus what I thought I had seen with my eyes, I actually grasped solely with the faculty of judgment, which is in my mind." He championed dualism — that is, the body works like a machine and obeys laws of physics; the mind does not. He asked, as we might today, how a non-material mind, as opposed to a brain, can influence a material body. He rejected appeal to ends, divine or natural, in explaining nature and proposed to proceed not "… as others usually do by way of aimless and blind enquires and more by luck than by skill but by following certain rules."

His proof of the existence of God may seem a bit convoluted to the modern ear. Man "… being imperfect, could have acquired the concept of perfection only from the perfect," that is, from God. Descartes argued that analysis by the mind is the essence of being. "*Cogito ergo sum*" — "I think, therefore I am."

He turned to science; all matter was assumed to be inert. This meant that a piece of matter had no propensity for moving itself — it was, in effect, dead. Thus the only way to get it to do anything was to apply to it some outside moving agency. Descartes rejected Aristotle's analysis that a cloth is red because it possesses redness; a fire is hot because it has warmth. He criticized these mere psychological impressions; one must look to the inherent qualities of matter. The only true idea of the nature of a body is geometrical extension of what matter really, in itself, is.

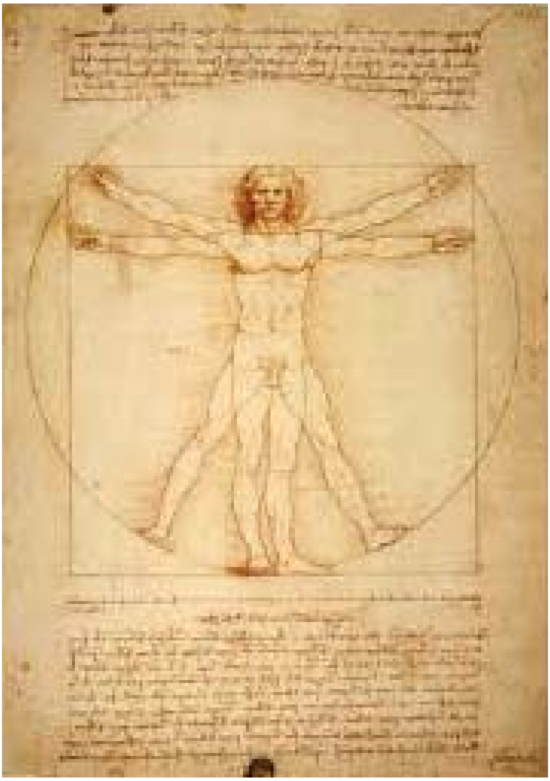
Descartes equated space with matter; hence there could be no vacuum, a view originally championed by Parmenides (Chapter A2). He attributed a straight, unbending flow to tiny particles thereby conserving momentum and a driving force on up to planetary motion. The "… action of light …" should "… operate in straight lines emerging from the luminous body." "… the water that they (fish) push before them does not push all the water in the pool indiscriminately; it pushes only the water which can best serve to perfect the circle of their movement and to occupy the place which they vacate." The sun is an appearance generated by the presence at the center of our system of matter that consists of especially small, fluid, and very rapidly moving particles; their jostling exerts pressure." "… it is not surprising that the particles of salt have a sharp and penetrating taste, which differs a great deal from that of fresh water; because they cannot be bent by the fine material that surrounds them, they must always enter rigidly into the pores of the tongue ...”

Peter Dear wrote that in “Descartes’ view of the natural world ... math-operational form of knowledge was capable of discussing, and no more.” “Descartes wanted to present explanations that could not (he hoped) possibly be challenged. In other words, he wanted certainty rather than mere opinion; his ideas were to be accepted for their truth, not simply for their likelihood or even mere ingenuity.” (*The Intelligibility of Nature: How Science Makes Sense of the World* (2006))

Like those of the Greeks and many others who preceded him (Chapter A2), many of Descartes’ explanations or models of science were “wrong,” given our contemporary understanding. One might ponder which of our models will be considered wrong in 2100 A.D. However, as will be elaborated, the important point is that he presented specific, reasonable ideas — the starting point for their replacement by better ones.

A8

The Scientific Revolution



Leonardo da Vinci's
"Vitruvian Man"

(Vitruvius ~50 B.C.
De architectura).

It is misleading to speak of "the" scientific revolution. Inflection points of insight occurred at different dates in different fields and in different countries of Europe; the sequence of chapters in Sections B (physics) and C (biology) to some extent reflect these different dates. Certainly 1543 is the reference for both physics, Copernicus, and for biology, Vesalius. If that were not enough, Pierre Ramus in 1543 published his *Animadversions on Aristotle*. Not only must the new be elaborated, the old must be revised.

Many arguments are, at core, semantic; this makes them no less important, but it does shift the discussion. Since 1600, frequently cited as the beginning of the scientific revolution, a term coined by Alexandre Koyré, the rate of discovery has increased and continues to increase. This begs the question of the significance of those discoveries, applications, or insights. Yet, asking this rate may pose the wrong question. Did this period mark a fundamental difference in the way Europeans viewed themselves and their physical environment? If so, was the revolution more cultural than scientific? Did the increased rate of discovery reflect a change in culture? If so, why did China or Islam not experience such a revolution? To anticipate Thomas Kuhn's *The Structure of Scientific Revolutions* (Chapter A11), were there exceptionally many or major shifts of paradigm during this century (~1600–~1700)?

Certainly the breadth of economic and intellectual activities expanded. Gutenberg's invention of a printing press with movable type (~1440) facilitated the distribution of the 95 theses (posted 1517) of Martin Luther.

Nation states such as France, Britain, Spain, Sweden, and the Netherlands acquired greater stability and the peaceful transfer of power from one ruler to the next was more assured. One might argue that some of these changes were driven by advances in engineering, e.g. ship building, but hardly by basic science. More persuasive, perhaps, is the inverse argument that noblemen and merchants provided support for scientists, as championed by Francis Bacon in his Solomon's house described in *New Atlantis* (1626, Chapter A6).

There are three, at least, rather distinct ways to think about changes in science. The first and the second deal with progression, and with progress, from qualitative and quantitative perspectives.

Though difficult in practice, one could in concept list and weight the scientific activities of each decade and plot the weighted sum as a function of time. Certainly from 1300 onward such a graph for science in Europe would have a positive second derivative. A revolution in science, or within a sub-discipline, might be identified by a significant change in slope. The third approach, to be discussed in Section D, deals with the more complex interactions of society and science.

A more nuanced approach might adopt a Kuhnian perspective and ask which of the scientific activities on the list contributed to a shift in paradigm, as opposed to the accumulation of more information within an existing framework, i.e. ordinary science.

By all three metrics science, especially physics, from 1600 to 1700 experienced a revolution. This chapter summarizes a few of those key events; their details will be discussed in subsequent chapters.

Herbert Butterfield (1900–1979) in *Origins of Modern Science* (1949) wrote that The Scientific Revolution "… outshines everything since the rise of Christianity and reduces the Renaissance and Reformation to the rank of mere episodes … [It is] the real origin both of the modern world and of the modern mentality. Alexandre Koyré (1892–1964) in *From the Closed World to the Infinite Universe* wrote in 1959 of "… the most profound revolution achieved or suffered by the human mind … since Greek antiquity." P. Williams and H.J. Steffens, in *The History of Science in Western Civilization* (3 Vols. 1978–79), wrote: "It is a unique event, having never occurred in any other place or time and its effect on the development of Western civilization ranks it among the greatest events of human history." Steven Shapin in 1996 offered a catchy introduction: "There was no such thing as the Scientific Revolution and this is a book about it," but he basically agrees.

Williams and Steffens continued that scholars left scholasticism, the barren study of a simplified Aristotle, and scientists began to study Nature "in the raw." They rediscovered Plato and redefined physical reality in terms of mathematics. Many components of society, from the Mediterranean to Britain, were engaging a more demanding and more rewarding world. Four of the major factors that laid the foundation for the scientific revolution were universities, exploration, the Renaissance, and the Reformation.

Many universities were established in Europe before or during the 1200s; the approximate dates are:

Bologna	1088
Paris	1150
Oxford	1167
Modena	1175
Palencia	1208
Cambridge	1209

Salamanca	1218
Montpellier	1220
Padua	1222
Toulouse	1229
Orleans	1235
Siena	1240

Some were administered and supported by the Church, others by student organization; Oxford and Cambridge were supported by the Crown. The early faculties addressed the "trivirium" of grammar, logic, and rhetoric; subsequently they added the "quadvirium" of arithmetic, geometry, astronomy, and music.

Students entered as young as age 14; about six years study led to a Master's degree. Faculties of law, medicine, and theology were added; a doctorate might be awarded after about eight years. Rediscovered Greek manuscripts, often translated to Arabic, were brought to the West, especially by scholars fleeing the fall of Constantinople in 1453. Although the curricula were limited and the study often focused on a corrupted Aristotelian scholasticism, these early universities shared common features and curricula; students and faculty could travel from one to another and feel at home. They survive to this day and evolved to set a rather standard pattern for universities throughout Europe, then the world.

The Renaissance is roughly dated ~1500–~1600; the scientific revolution, ~1600–~1700. Whatever spans are chosen, the important point is that the Renaissance preceded the revolution. In one sense the Renaissance respected Greek scholarship; the revolution rejected much of it. One is left to wonder in what ways the Renaissance affected science?

There were several renaissances; the fever spread north from Italy. Giotto (1267–1337) employed a sort of linear perspective and achieved a natural reality in painting unknown to his contemporaries. Dante Alighieri (1265–1321) in Florence wrote in the vernacular to an increasingly literate citizenry. Petrarch (1304–1374), perhaps the leading intellect of his time, revisited classical manuscripts. Filippo Brunelleschi (1377–1446) and Alberti (1404–1472) drew and wrote sophisticated works about architecture.

Merchants of Florence, for example Lorenzo de' Medici, developed complex practices of finance and commerce; they were quite anti-monarchical. Many became patrons of the arts. One still marvels today at the brilliance of Leonardo da Vinci (1452–1519) and Michelangelo (1475–1564), appropriately designated "renaissance men."

Pico della Mirandola wrote of human dignity, *De hominis dignitate* (1486). Niccolò Machiavelli (1469–1527) and Thomas More (1478–1535) contemporary government. In 1543, both Copernicus in *De Revolutionibus* (Chapter B3) and Andreas Vesalius in *De humani corporis fabrica* (Chapter C2) questioned the received wisdom of Ptolemy and of Galen, respectively.

This was the age of discovery. There had been voyages to Somalia by the Chinese in the 800s (Chapter A3); the Vikings first settled Iceland in 865. Marco Polo returned to Venice in 1271 to reveal his, and his father's, adventures; the Europeans were aware of the fabulous spice islands. In 1330, Jodanus de Severec established the first French missions in India. In 1402, Bethencourt founded the first European settlement in the Canary Islands, the launching point for Columbus' voyage to the "Indies" in 1492. In 1515, Balboa (1475–1519) walked over Panama to view the Pacific. Magellan (1480–1522) was killed in the Philippines; only *Victoria* of his five ships completed the first circumnavigation of the globe. The horizons of Europeans had been expanded, as never before and, one might argue, as never since.

Perhaps more important, their internal horizons were changing. Working in both Strasbourg and Mainz, Johannes Gutenberg (~1398–1468) developed a printing press with movable type about 1439. He printed many copies of his Gutenberg Bible; perhaps more important, his press could produce lots of cheap pamphlets. Several questioned practices of the Church. How would one compare the relative impacts of Gutenberg and Google?

There were many conflicts within the Catholic Church. For example, the Albigensian Crusade (1209–1229) suppressed Catharism in Languedoc. However, this was not a direct antecedent of the Protestant reformation. John Wycliffe (1320–1384) received this doctorate in theology and became master of Balliol College, Oxford, in 1361. He was critical of the Church's accumulation of wealth as elaborated in his 18 theses and *Summa Theologiciae*. He translated the Bible into vernacular English in 1382. His open criticism of the Church served as a model for subsequent reformers. Jan Hus (1372–1415) of the Moravian Brethren was promised safe passage to the Council of Constance, then burned at the stake. The Council ordered that Wycliffe's body be exhumed and burned posthumously.

Martin Luther (1483–1546) had preached against the sale of indulgences and against simony, the purchase of positions within the Church. He sent his 95 theses (*Disputation of Martin Luther on the Power and Efficacy of Indulgences*) in 1517 to his bishop, Albert of Mainz. He protested in 1520: "Hier stehe Ich, Ich kann nicht anders" (Here I stand; I cannot do otherwise) and was excommunicated in 1521. The Diet of Worms, 1521, forbade anyone from this time forward to dare, either by words or by deeds, to receive, defend, sustain, or favor Martin Luther.

Each of the following — Huldrych Zwingli, executed in Zurich; John Calvin, who moved from Paris to Geneva; and John Knox of Scotland — had his own message of reformation. There was hardly a united front against the Catholic Church. The Church of England separated from Rome in the period 1529–1536. Thomas More stood opposed and was beheaded by order of Henry VIII of England. The Council of Trent (1545–1563) condemned the Protestant heresies. About 50,000 Huguenots were killed in Paris in the St. Bartholomew's Day massacre, 1572. Henry IV of France granted some religious freedom to the Huguenots in the Edict of Nantes, 1598. These rights were revoked by the Edict of Fontainebleau, 1685.

In the Thirty Years' War (1618–1648), the Catholic House of Habsburg, supported by Spain and Austria, fought the protestant princes of Germany, supported by Denmark, Sweden, and France. The slaughter killed about 35% of the German population. In the Treaty of Westphalia, 1648, all parties recognized the Peace of Augsburg, 1555; each prince had the right to determine the religion — Roman Catholicism, Lutheranism, or Calvinism — of his state. All guarantied the practice of other faiths in public during allotted hours and in private at will. Pope Innocent X was not amused and declared the treaty "… null, void, invalid, iniquitous, unjust, damnable, reprobate, inane, empty of meaning and effect for all times."

Europe was busy from 1500 to 1700. Important discoveries — changes in paradigm, to anticipate Kuhn's terminology — were made in science. The correlation is irrefutable; as always, the question is causality.

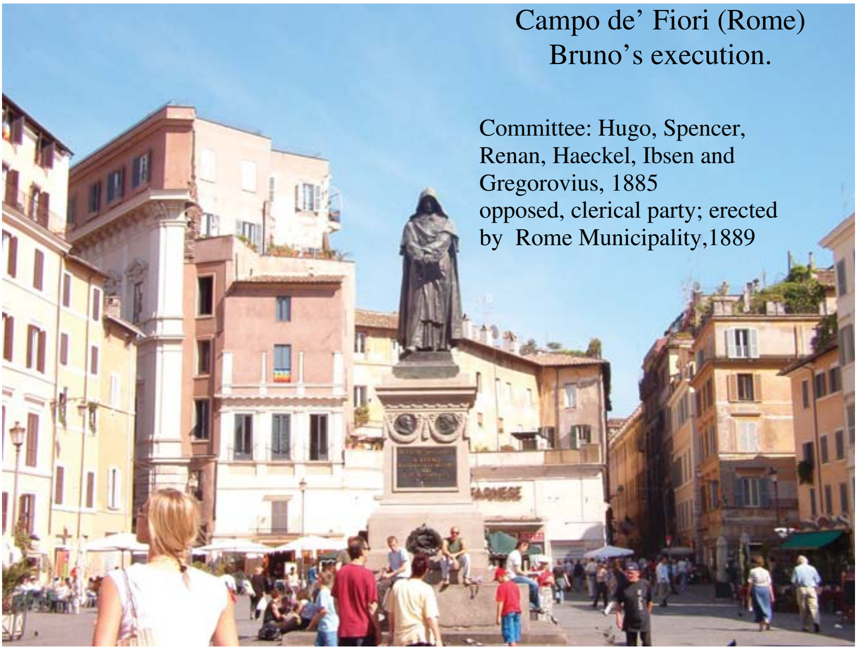
As will be elaborated in the following chapters, a new physics was being born. Copernicus (1473–1543) in *De revolutionibus orbium celestium* proposed a heliocentric system in 1543. Gilbert (1544–1603) discussed magnetism in *De magnete* (1600) and suggested a d^{-2} force relationship. Bacon (1561–1626), in the *Novum organum* (1620), discussed the inductive method, but more importantly championed a research institute devoted to applying "works" to the benefit of society (Chapter A6). Kepler (1571–1630) described the elliptical orbits of the planets and the ratio of the square of the period to the cube of the major axis of the orbits of two planets ($T_1^2/T_2^2 = r_1^3/r_2^3$). Galileo (1564–1642) observed four of the moons of Jupiter and recorded the movement of "spots" across the surface of the sun (Chapter B3). He noted that two masses fall at the same velocity under the same gravitational force in Pisa and supposedly worldwide. He combined the two rectilinear motions of Aristotle into the curved path of a cannon ball. Descartes (1596–1650) elaborated on the deductive method, developed analytical geometry, and derived the equation describing the trajectory of a projectile. Newton (1643–1727), in his *Principia* (1687), assumed that Gilbert's inverse square law applied to gravitational attraction: $F = k \cdot m_1 \cdot m_2/d_{12}^2$ (force of attraction is proportional to the product of the two masses divided by the square of their distance apart). He proposed his three laws of motion: A body moving in a straight line continues straight until another force acts upon it. Acceleration equals the force acting upon a body divided by its mass: $F = m \cdot a$. For every action, there is an equal and opposite reaction. He developed a form of calculus, so-called fluxions, and from his three laws derived the orbits described by Kepler. Most importantly he proposed that these laws were universal (Chapter B4).

Biology experienced major advances: Vesalius (1514–1564) in *De humanis corporis fabrica* (1543) corrected several errors in Galen's anatomy. His work was followed by that of a series of distinguished anatomists, most working at the University in Padua, who explored human anatomy in ever finer detail. Harvey (1578–1657) studied at Padua and several other universities on the continent. In his *De motu Cordis* (1628) he correctly described the complete circulatory system. He found no hole in the septum of ventricles, or of the auricles; he postulated a capillary bed, subsequently visualized by Malpighi, that connects the arterial and venous systems (Chapter C3).

One might rephrase the question of the origin(s) of the scientific revolution. Thomas Carlyle (1795–1881) wrote: "Universal history, the history of what man has accomplished in this world, is at bottom the History of the Great Men who have worked here." In contrast, Otto von Bismark (1815–1898) wrote: "The statesman's task is to hear God's footsteps marching through history, and to try to catch on to His coattails as He marches past." Why did God choose to place his scientific steps in Western Europe at this time?

A9

The Church and Science



Survival was the main challenge for the early Christian Church. This depended on establishing a doctrine and suppressing heresy. The elaboration and articulation of doctrine was a significant challenge. Broad intellectual curiosity about science or other frivolities was not encouraged and often suppressed.

By ~600, the Church was a bit more secure. The bishop of Rome was called the Pope, at least in Western, Catholic Europe.

Inevitably members of the priesthood and general laity were curious about the natural world. These involvements did not threaten the Church; they were in general tolerated if not explicitly supported. By the new millennium, men like Roger Bacon and Thomas Aquinas were thinking more broadly; there was no conflict between their science and their Church. Modest advances in alchemy, metallurgy, and engineering were generally embraced. Monasteries were often centers of technical expertise, especially in agriculture and medicine. However, Luther's posting (apocryphal or not) of his 95 theses in 1517 did not make the Church more tolerant. Most of the distinguished scientists of the scientific revolution — da Vinci, Copernicus, Vesalius, Kepler, Brahe, Galileo, Harvey, Huygens, Descartes, Newton, Leibniz — expressed their commitment to the Church and the true faith.

The Draper–White thesis argued that for the preceding three centuries, 1600–1900, religion and science had been in conflict and science had inevitably won. Several contemporary historians have revised this triumphalist or whiggish interpretation. They concede the conflict between Galileo and Pope Leo X as well the opposition to Darwin and Wallace's theory of evolution; however, most religious authorities, most of the time have not only accepted but also championed science, ever more so in recent years. The 76 members, including several Nobel Laureates, of the Pontifical Academy (re-established in 1936) are committed to promoting science and to exploring the relevance of science to epistemological concerns. The (in)tolerance of the Church has not been constant over the centuries; both critics and defenders can choose from many examples.

The historian can select, and accurately portray, examples to support one interpretation of a complex story. The following examples reflect, hopefully, a balanced view of the evolving relationship between science and the Catholic Church.

Hildegard von Bingen (1098–1179), the tenth child of a family of free nobles, was "offered" to the church as a tithe. She was elected magistra by her fellow nuns and founded a second convent for her nuns at Eibingen in 1165. In *Causae et curae*, she described tinctures, herbs, precious stones and the cosmos; she concluded "… all things put on earth are for the use of humans."

Roger Bacon (~1214–~1294) was a Franciscan friar; he then became a Master at Oxford. Bacon recorded the spectrum from white light passed through a "prism" and opposed blind obedience to authority. His *Opus majus* and *Opus minus* included a critique of Aristotle and essays on mathematics, optics, alchemy, gunpowder, and astrology. He was applauded by his students as Doctor Mirabilis and was valued by colleagues and by the Church.

Andreas Osiander prepared an unauthorized preface to Copernicus' *De revolutionibus orbium coelestium* (On the Revolutions of the Heavenly Spheres, 1543); he cautiously noted that it did not reflect physical reality, but was a device for computing orbits (Chapter B3). Nonetheless, the Church in 1616 placed it on its *Index librorum prohibitorum* (List of prohibited books) and suspended *De revolutionibus* for correction; it was declared "… false and altogether opposed to the Holy Scripture." Paracelsus (1493–1541) wrote in his discussion of alchemy "This is the way that nature proceeds with us in God's creatures…"

Miguel Serveto Conesa (1511–1553) studied with Dominican friars and was the first European to discuss pulmonary circulation. He was condemned by the Catholic Church as a religious dissenter and anti-Trinitarian. Jean Calvin wrote: "Servetus has just sent me a long volume of his ravings. If I consent he will come here, but I will not give my word for if he comes here, if my authority is worth anything, I will never permit him to depart alive." He was arrested by Calvin and burned at the stake in Geneva. His conflict had nothing to do with pulmonary physiology; however, his interest in science hardly offered any protection.

Giordano Bruno (1548–1600) was ordained as a Dominican in 1572, then left the Order and was excommunicated. He championed his own mystical heliocentrism and a pantheistic hylozoistic system (all matter is living). He was arrested by the Church in 1592 and transferred to Rome next year. His trial lasted seven years. He was convicted of:

- Holding opinions contrary to the Catholic Faith and speaking against it and its ministers.
- Holding erroneous opinions about the Trinity, about Christ's divinity and Incarnation.
- Holding erroneous opinions about Christ.
- Holding erroneous opinions about Transubstantiation and Mass.
- Claiming the existence of a plurality of worlds and their eternity.
- Believing in metempsychosis and in the transmigration of the human soul into brutes.
- Dealing in magic and divination.
- Denying the Virginity of Mary.

Cardinal Bellarmine demanded full recantation; Bruno refused. Pope Clement VIII denied his appeal. Bruno defiantly responded: "Perhaps you, my judges, pronounce this sentence against me with greater fear than I receive it."

He was gagged, tied to a pole naked, and burned at the stake, in 1600, in Campo de' Fiori, Rome. All of his works were placed on the *Index* in 1603. John Paul II acknowledged the Church's error in 2000 and expressed "profound sorrow." Bruno was not executed because of his belief in heliocentricity but nonetheless, it had a real chilling effect.

Galileo Galilei (1564–1642) endorsed heliocentrism in his *Dialogue Concerning the Two Chief World Systems* (1632). Cardinal Roberto Bellarmine enjoined Galileo to neither "hold nor defend" heliocentrism in 1616. The latter was ordered to appear before the Holy Office in Rome in 1632. He argued that heliocentrism was not contrary to Scriptures. Galileo stood trial on suspicion of heresy in 1633. He was found guilty; his sentence demanded that he recant his heliocentric ideas; this he did. He was ordered imprisoned; this sentence was commuted to house arrest. His *Dialogue* was added to the *Index*, but was removed in 1835. He is said to have muttered upon hearing his sentence: "*Eppur si muove*" (and yet it moves).

Francis Bacon wrote in *The Essays: Of Atheism* (1625): "… a little philosophy inclineth man's mind to atheism; but depth in philosophy bringeth men's minds about to religion." René Descartes' *Discourse on the Method* (1637) was placed on the *Index* in 1663. Robert Boyle (1627–1691) was director of the East India Company and promoted Christianity in the East. He established the Boyle lectures to defend Christianity against "notorious infidels, namely atheists, deists, pagans, Jews and Muslims." Antony van Leeuwenhoek (1632–1723) was a Dutch Calvinist. He regarded his early microscopic studies of capillaries as proof of the great wonder of God's creation. Jan Swammerdam (1637–1680) argued that studying the Earth's creatures revealed the greatness of God. Isaac Newton (1642–1727) conceded that: "Gravity explains the motions of the planets, but it cannot explain who set the planets in motion. God governs all things and knows all that is or can be done."

Thomas Aikenhead (~1678–1697), a young student at the University of Edinburgh, was charged with blasphemy. "That … the prisoner had repeatedly maintained, in conversation, that theology was a rhapsody of ill-invented nonsense …" "That he rejected the mystery of the Trinity as unworthy of refutation; and scoffed at the incarnation of Christ." Aikenhead pleaded in vain for mercy on the gallows.

Carl Linnaeus (1707–1778) responded to the charge of impiety by the Archbishop of Uppsala: "It is not pleasing that I place Man among the primates, but man is intimately familiar with himself." "If I called man a simian or vice versa I would bring together all the theologians against me." Georges-Louis Leclerc, Comte de Buffon (1707–1788), denied Noah's flood. He was condemned by the Church and his books burned.

Joseph Priestly (1733–1804), one of the founders of Unitarianism, was branded an atheist in 1782. His *The Importance and Extent of Free Enquiry* (1785) roused a mob to burn his house and church. He fled England for the United States in 1791. The Priestley Medal, established in 1922, is the highest award of the American Chemical Society. Robert Schofield maintained that "Priestley was never a chemist; in a modern, and even a Lavoisian, sense, he was never a scientist. He was a natural philosopher, concerned with the economy of nature and obsessed with an idea of unity, in theology and in nature."

Louis Pasteur (1822–1895), near the end of his distinguished career, said: "The more I know, the more nearly is my faith that of the Breton peasant." Johann Gregor Mendel (1822–1884) performed his "Experiments on plant hybridization" in the Augustinian Abbey of St. Thomas in Brno, establishing the science of genetics (*Proc. Nat. Hist. Soc. of Brünn*, 1866). His subsequent duties as abbot left him no time to continue his science.

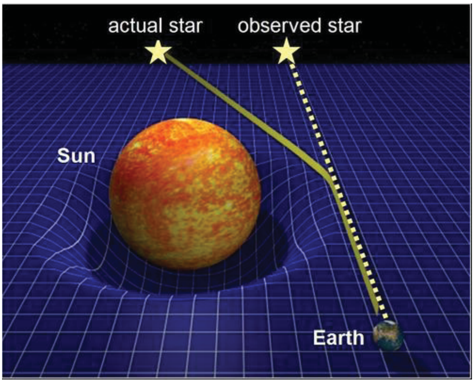
These varied examples do not permit a simple conclusion; however, several themes emerge. Most scientists, whether Catholic or Protestant, professed a true belief in God. Many felt that their science revealed the wonders of God's creations. The worst conflicts with the Church often involved personal disputes or heresies only peripherally related to science. The two real challenges to doctrine and beliefs were heliocentricity (Chapter B3) and evolution

(Chapter C14). The response of the Church to perceived dissenters became less violent with the passage of time.

Karl Popper (Chapter A10) emphasized the "… distinction between a scientific revolution and the ideological revolution which may sometimes be linked with it." He referred to Copernicus and Darwin: "… in these two cases a scientific revolution gave rise to an ideological revolution […] ideological insofar as they both changed man's view of his place in the universe." The four basic equations of electricity and magnetism (Chapter B8) as summarized by Maxwell (1831–1879) were of corresponding scientific importance; however, they were not "ideological."

A10

Falsifiability: Karl Popper



The deflection of starlight by the mass of the Sun.

Those who favor an operational definition, or characterization, of science often turn to *The Open Society and Its Enemies,* by Karl Popper. In essence he argued, as had several before him without full elaboration, that a theory in science can never be fully verified or proven. Its validity rests on the number and stringency of attempts to falsify it. In practice, a "control" experiment can be described as an attempt at falsification.

Sorry, there is no clear definition of or distinction between generalizations, patterns, hypotheses, theories, and laws. The validity or accuracy of these terms often depends, implicitly or explicitly, both on the range of phenomena discussed and on the attempts at falsification.

Of greater concern is how one applies falsification to historical sciences, such as (aspects of) astronomy, geology, and especially biology. Usually one cannot repeat the experiment under different conditions — the standard procedure in falsification (or verification). Given the spectrum of observations and experiments on components of the system, one seeks the most parsimonious interpretation, i.e. with the fewest and least improbable assumptions — one statement of Occam's razor (*lex parsimoniae*).

Popper did not explicitly address engineering and medicine. Even so, it is certainly good practice to make test runs or clinical trials before going to market.

Rarely does one elaborate on a new idea or make a discovery without precedent. The discovery of X-rays in 1895 by Wilhelm Röntgen (1845–1923) is a lovely exception. Inherent in most theories are implicit or explicit predictions. As critics of Popper, for example Thomas Kuhn (Chapter A11), argue, the failure of one of these predictions is seldom so decisive as to falsify the theory. Certainly a great deal depends on context and on whether a modification of the theory might ensure its survival.

Pascal's brother-in-law, Florin Périer, took a mercury barometer designed by Evangelista Torricelli (1608–1647) to the top of Puy de Dome, 1,000 m high, and left its identical mate at a lower level. He noted the difference "in barometric pressure of about seven cm; air had mass as predicted." Had no difference been observed, the concept of air having mass should have been accepted as falsified by the community.

Darwin himself set the standard when he acknowledged: "If it could be demonstrated that any complex organ existed which could not possibly have been formed by numerous, successive, slight modifications, my theory would absolutely break down." (*Origin of Species*, p. 171)

Popper frequently referred to the idea that "All life is problem solving," and explored how one goes about characterizing and solving problems in science, then in society. He concluded by arguing that an "open society" is better equipped to evaluate, or attempt to falsify, policies than is a rigid, authoritarian society. He did not argue that the policies of an open society are better than those of an authoritarian one. Setting and evaluating policy is an ongoing and never-ending process. In an open society one can more easily acknowledge errors and make corrections.

Popper continued his criticism of authority: "Knowledge in this objective sense is totally independent of anybody's claim to know; it is also independent of anybody's belief, or disposition to assert, or to act. Knowledge in the objective sense is knowledge without a knower; it is knowledge without a knowing subject." The authority of the knower is irrelevant (Notturno, *Science and the Open Society: The Future of Karl Popper's Philosophy*, 2000).

He was critical of induction as a valid way of doing science, without acknowledging the distinction made by Francis Bacon, who offered the analogy that ants merely gather, a simple accumulation of observations. However, bees not only gather but also use their own creative energies to synthesize honey.

Popper asserted that "Scientific knowledge need not be justified." Having dismissed induction, as well as *a priori* knowledge, he explored "critical rationalism" and concluded that falsifiability is its core. "Science appeals to experience to criticize its theories and not to justify them." He quoted Hume:

> "The only thing that the validity of an argument tells us regarding the truth of its premises and conclusions is that it cannot be the case that the premises are true and the conclusions are false."

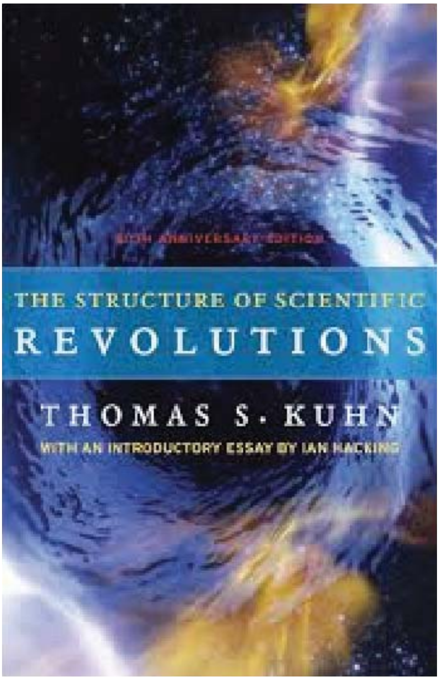
Popper heard Einstein's lecture in 1919 in which he explained "How theory (relativity) might be tested." The *bending* of starlight passing near a massive sun would cause the star's apparent position to a viewer on Earth to be shifted by a calculable amount. During the solar eclipse on 29 May 1919, Arthur Eddington (1882–1944) sent expeditions to the island of Príncipe, off the west coast of Africa, and to Sobral, in Brazil, to observe stars in the Hyades cluster. The predicted deviation of about 1.0 arc seconds was observed (Eddington and Dyson, 2009). This test, i.e. attempt to falsify, inspired Popper to elaborate on the idea: "Scientists cannot discover and justify their theories through observation. But they can invent their theories as speculative solutions to their problems and then test them against observation and experience."

He argued for an ongoing process of proposals, leading to theories, leading to criticism (attempts at falsification). This would lead to new proposals and to new theories. He did not elaborate on the creative process whereby the experiments and/or observations might lead to new proposals.

Popper was a professor at the London School of Economics from 1949–1969. Perhaps his most distinguished student was George Soros, the extremely successful and wealthy investor. Soros questioned the application of the term, *science*, to social studies such as economics, because the objects of study, human beings, are themselves aware of such studies and could modify their behaviors accordingly.

A11

Paradigm: Thomas Kuhn



Thomas Samuel Kuhn
(1922–1996).
Shift happens.

Thomas Kuhn, in *The Structure of Scientific Revolutions* (1962), argued that from a historical perspective, fields of science can be viewed as functioning within a generally accepted, conceptual and technical framework — a paradigm — punctuated by abrupt shifts. He cited examples — Copernican heliocentricity, dynamics of Galileo and Newton, the overthrow of phlogiston by Lavoisier, Darwinian evolution, and Einstein's relativity — that are consistent with his formulation. These generally acknowledged revolutions were preceded by an accumulation of observations and/or experiments that were inconsistent with the prevailing paradigm. They were made by younger men not yet professionally invested in the old paradigm. Two of these examples, heliocentricity and dynamics, were major components of the scientific revolution of 1600–1700. Further, Kuhn argued that a single inconsistency or falsification did not lead to the rejection of the old theory as posited by Popper.

Several concerns have been expressed. Did some discoveries or theories, e.g. radioactivity and nuclear decay, replace old ones, i.e. was there a paradigm shift, or was there no pre-existing paradigm? If not, would that imply "pre-science" in that nascent discipline? The theory of plate tectonics, as the mechanism underlying continental drift, was quickly accepted by both young and old soon after "Magnetism in the Sea-floor" was published by Frederick Vine in 1963. Advances in molecular and cellular biology since 1950 have been dramatic. Did they involve the accumulation of new data, "normal science," at an accelerated pace or did they reflect a paradigm shift(s)?

Kuhn had to defend himself from critics who argued that he had acknowledged that the choice of paradigms was influenced by factors other than objective evaluation of available data and hence scientists held no privileged position of rationality relative to humanists.

Kuhn wrote that "… normal scientific research is directed to the articulation of those phenomena and theories that the paradigm already supplies." It is "puzzle-solving" with one of three goals:

1) determination of significant fact; 2) matching of fact with theory; 3) articulation of theory. Few scientists would disagree.

Thomas Kuhn (1922–1996) completed his Ph.D. in physics at Harvard in 1949. He was encouraged by James Conant, president of Harvard, to pursue the history of science. *The Structure of Scientific Revolutions* was published in 1962 and generated controversies that are still relevant a half century later. A summary of his arguments puts its antecedents and reverberations in perspective.

Much of Kuhn's thesis concerned the characterization of a "paradigm" and in turn, a paradigm shift. He did not give a concise, explicit definition but elaborated on many characteristics. He referred to "pre-science" in which there is no paradigm. A paradigm, characteristic of normal science, within any (sub)discipline consists of the:

- puzzles that the community tries to solve
- concepts and theories that practitioners consider important
- techniques and procedures commonly employed
- ways in which results are summarized and presented
- patterns of interactions among members of that community.

Just as the characteristics of a paradigm are a bit fluid, so the range within any discipline varies. "… the existence of a paradigm need not even imply that any full set of rules exists." These characteristics are not explicitly stated; as young scientists enter the field they pick them up.

Kuhn then elaborated on circumstances that presage a paradigm shift. He did not address the origin(s) of the original paradigm, the inferred essential step proceeding from pre-science to science. The community may encounter situations both in science and in infrastructure that are not accommodated by the existing paradigm. Herbert Butterfield in 1949 (*Origins of Modern Science*) had already described the challenge "… where one cannot escape an anomaly, and the theory has to be tucked and folded, pushed and pinched, in order to make it conform with the observed facts." Kuhn continued: "To be accepted as a paradigm, a theory must seem better than its competitors, but it need not, and in fact never does, explain all the facts with which it can be confronted."

Most scientists are not offended by Kuhn's statement that "Mopping-up operations are what engage most scientists throughout their careers." This mopping-up is equated with "puzzle solving." "It is no criterion of goodness in a puzzle that its outcome be intrinsically interesting or important." A "… striking feature of the normal research problems … is how little they aim to produce major novelties, concepts or phenomena." "Even the project whose goal is paradigm articulation does not aim at the *unexpected* novelty." This would be a tall order for any scientist.

These unanticipated, and unanticipatable, novelties lead to crisis within the community. "The significance of crises is the indication they provide that an occasion for retooling has arrived."

He continued: "… a scientific theory is declared invalid only if an alternate candidate is available to take its place." "Nevertheless, anomalous experiences may not be identified with falsifying ones. Indeed, I doubt that the latter exist." "No process yet disclosed by the historical study of scientific development at all resembles the methodological stereotype of falsification by direct comparison with nature." "They (scientists) will devise numerous articulations and *ad hoc* modifications of their theory in order to eliminate any apparent conflict."

"Once a first paradigm through which to view nature has been found, there is no such thing as research in the absence of any paradigm. To reject one paradigm without simultaneously substituting another is to reject science itself." "… paradigm-testing occurs only after the persistent failure to solve a noteworthy puzzle has given rise to crises."

Kuhn wrote that these crises "close in one of three ways": i) "… normal science ultimately proves able to handle the crisis …"; ii) "The problem is labeled and set aside for future generations …"; iii) "… the emergence of a new candidate for paradigm …"

"Almost always the men who achieve these fundamental inventions of a new paradigm have been either very young or very new to the field whose paradigm they change." (Contemporary feminists might subject him to a different sort or paradigm shift.)

Kuhn argued that in order to do science the community must have a paradigm — a shared language, common goals, and agreed problems. No matter that the paradigm is subsequently replaced; the information, protocols, and techniques would prove valuable working in the new paradigm. He cited Francis Bacon: "Truth emerges more readily from error than from confusion."

As did Popper, Kuhn extended his model beyond science. "In both political and scientific development the sense of malfunction that can lead to crisis is prerequisite to revolution." "Political revolutions aim to change political institutions in ways that those institutions themselves prohibit."

The following statements generated the greatest interest outside of the research community. "Like the choice between competing political institutions, that between competing paradigms proves to be a choice between incompatible modes of community life. Because it has that character, the choice is not and cannot be determined merely by the evaluative procedures characteristic of normal science …" "… like the issue of competing standards, that question of values can be answered only in terms of criteria that lie outside of normal science altogether, and it is that recourse to external criteria that most obviously makes paradigm debates revolutionary." Scholars outside of the research community cited this to argue that scientists were no more analytical or rational and that they should relinquish their sense of privilege. Kuhn defended himself: "My remarks have been misconstrued." "In debates over theory-choice; once premises have been accepted — the only analysis is one of logic. In contrast discussion of the premises inevitably introduces subjective value judgments. However, this does *not* mean that logic is not a factor."

Imre Lakatos wrote in *Falsificationism and the Methodology of Scientific Research Programs* (1962): "The clash between Popper and Kuhn is not about a mere technical point in epistemology. It concerns our central intellectual values, and has implications not only for theoretical physics but also for the underdeveloped social sciences and even moral and political philosophy."

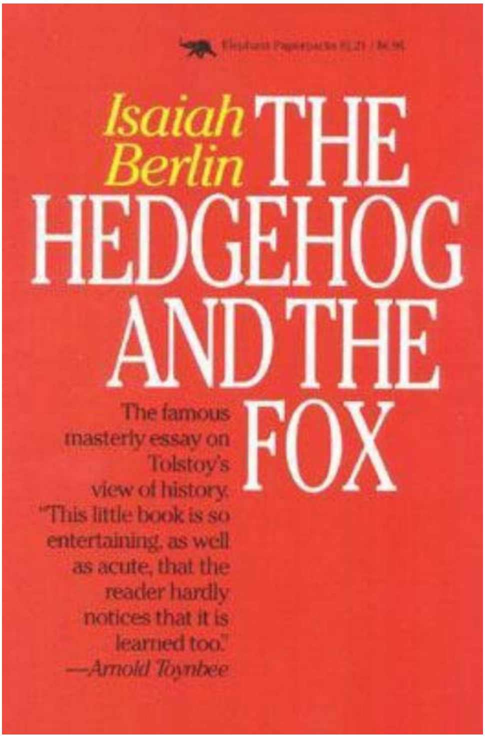
In contrast, Paul Feyerabend in *How to Defend Society against Science* (1978) was dismissive: "[Kuhn's] ideology of science could only give comfort to the most narrow-minded and the most conceited kind of specialism. It would tend to inhibit the advancement of knowledge. And it is bound to increase the anti-humanitarian tendencies which are such a disquieting feature of much of post-Newtonian science."

The term *paradigm shift* is now so widely applied as to have lost its original meaning. Yet, historians still ask whether a change or an advance in a (sub)discipline of science reflects a shift of paradigm or accumulation of insight and technique within *ordinary science*. Is this a meaningful question?

The most important concern from the perspective of this book is whether a synthesis of Popperian and Kuhnian perspectives informs contemporary science, and especially biology. Both implicitly address "pure" science. One is left to wonder whether their analyses and arguments apply to engineering and medicine.

A12

Two Cultures: C.P. Snow



After Archilochus "the **fox** knows many things, but the **hedgehog** knows one big thing."

C.P. Snow, British physicist turned novelist, delivered the Rede Lecture in 1959. Much of his lecture addressed education in Britain and compared it with the upstart Russian and American systems. He also said that "… the intellectual life of the whole of Western society is increasingly being split into two polar groups," scientists versus humanists, and that the two were separated by a "gulf of mutual incomprehension." "The non-scientists have a rooted impression that the scientists are shallowly optimistic, unaware of man's condition." Snow subsequently acknowledged that his introductory remarks contrasting the intellectual traditions and mutual incomprehension of the humanities and of the sciences were a great simplification.

He wrote in *The Two Cultures: A Second Look* (1964): "In fact, those two revolutions, the agricultural and the industrial-scientific, are the only qualitative changes in social living that men have ever known." He further argued that: "Industrialization is the only hope for the poor," and elaborated "… if you go without much food, see most of your children die in infancy, despise the comforts of literacy, accept twenty years off your own life, then I respect you for the strength of your aesthetic revulsion [of industrialization]." One can argue that his defense of science and its impact was a gross simplification, yet anyone yearning for a simpler, pre-industrial life must address his arguments.

The phrase “two cultures” was catchy and the ground fertile. For the past half-century numerous scholars have addressed implied binary divisions within society, or within the academy, or even within a discipline, e.g. history vs. political science. The idea was extended to “culture wars,” then to all sorts of scholarly “wars.” If said scholars had actually experienced the horrors of war, they might not have used the term so glibly.

Snow extended this binary concept: “Pure scientists and engineers often totally misunderstand each other.” He acknowledged that many others, for example Jacob Bronowski in *Science and Human Value* (1956), had already addressed these issues. Snow argued: “But I believe the pale of total incomprehension of science radiates its influence on all the rest.”

Snow did, however, capture a kernel of truth. During the Renaissance the very small fraction of the population who were literate probably considered natural history to be an integral part of their intellectual world. The encyclopédistes of 18th century France felt that at least a few individuals could grasp all of human knowledge. This knowledge continues to expand; few scientists today are familiar with the full breadth of science, few humanists with all of the arts. Does the concept of “two cultures” simply reflect the breadth of contemporary knowledge and our relatively few, $\sim 10^{11}$, neurons? Or is there, on average, a real and significant difference between what scientists value and the way that they think in comparison with the rest of the population? At higher resolution, is there a difference between biologists and physicists, or between those focused on application (engineers and physicians) and those seeking basic knowledge?

Snow’s rather simple formulation basically asked how the humanist and the scientist might better understand and value the other’s work, that is, how to encourage and appreciate the dialog. Other scholars, most notably E.O. Wilson in *Consilience:*

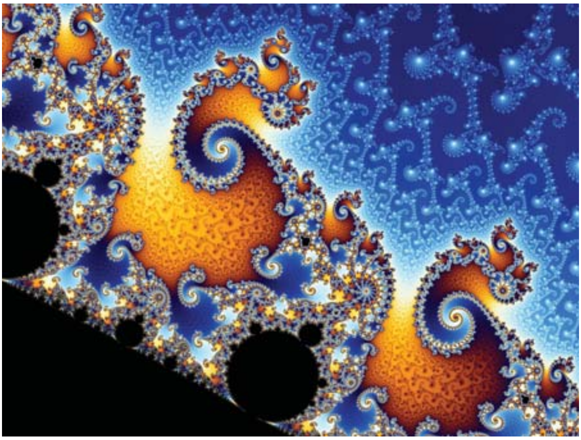
The Unity of Knowledge (1998) have addressed a fundamentally different but related question. Is the nature of knowledge and understanding in the humanities and in the sciences inherently different; will it be in the future? Might future advances in molecular and neurobiology actually permit one to make meaningful comments about the humanities based on science? Would (aspects of) the humanities be subsumed under the broader umbrella of science?

It is often easier to develop an argument assuming a bimodal distribution — blue vs. red; left vs. right — when in fact there is no cleavage or the distribution is tri-modal. The legend of the Hedgehog and the Fox, attributed to Archilochus, says "… the fox knows many things, but the hedgehog knows one big thing …" Isaiah Berlin in 1953 examined the single-minded focus of Dosteovsky versus the range of interests shown by Tolstoy. Granted, this division is a gross simplification; however, it does facilitate a description of different perspectives. Few people or institutions are purely blue or red, but some complex mixture and synthesis — shades of purple.

The above-mentioned encyclopédistes were a group of 18th century writers in France who compiled and wrote the *Encyclopédie*, edited by Denis Diderot and Jean le Rond d'Alembert. Many were part of the intellectual group known as the philosophes. They promoted the advancement of science and secular thought and supported tolerance, rationality, and the open-mindedness of the Enlightenment. One would hardly apply the epitaph "two cultures" to them or to their encyclopedia. It is difficult to accept that this perspective is gone forever, since it is the theme of this book.

A13

Emergence



Mandelbrot set.

Several inter-related terms or concepts are essential to discussions of science. There is not complete agreement about their definitions and implications; the following reflect something of a consensus.

Reductionism is associated with simplification. Structures or properties at one level are described or understood by characteristics of a more basic level. This inter-level approach has been equated with fundamental understanding in physics.

Complexity refers to a system or process that can be adequately described only by many degrees of freedom and a broad range of values of the associated parameters.

Predictability refers to the ability to predict the characteristics of a system at some future time, given any or all of the characteristics of that system at an earlier time.

Determinism refers to a system or a process whose future state can, in principle, be predicted from knowledge of its state at an earlier time.

Chaos refers to a system that is deterministic but unpredictable in practice due to its extreme dependence on initial conditions.

Quantum Uncertainty derives from the "Uncertainty Principle" of Heisenberg, $\Delta x \cdot \Delta p$ (or $\Delta E \cdot \Delta t$) $> \hbar/2$.

Randomness: the outcome of a single coin toss is probabilistic, or random; the distribution of many tosses is highly predictable.

Emergence refers to a property of a system that is assumed to have arisen from more fundamental characteristics but cannot be explicitly derived or predicted from those characteristics.

Vitalism in its various forms ascribes properties to living systems that are unique and not derivable from the properties of its non-living components.

Reductionism: Steven Weinberg (Nobel Laureate, 1979) was certainly right (almost): "All the explanatory arrows point downward, from societies to people to organs, to cells, to biochemistry, to chemistry, and ultimately to physics." For many this is the essence of, if not the definition of, science. As will be elaborated, most molecular and cellular biology can be cast in this reductionist framework. Evolutionary biology requires quite a different perspective. The wedding of these two views makes contemporary biology *especially* exciting!

Complexity refers to a system or process that can be adequately described only by many degrees of freedom and by a broad range of values of the associated parameters. The skill of a good scientist is reflected in his choice of a simple system amenable to investigation with available techniques. This pushes the more complex problems on to the next generation, hence Vannevar Bush's *Endless Frontier* (Chapter C16). Many complex systems in biology are now analyzed by statistical analysis of massive data sets. Systems that have emergent properties are always complex.

Predictability (or of greater concern, unpredictability) or *determinism* refers to the ability to predict the characteristics of a system, often but not necessarily *complex*, at some future time, given any or all characteristics of that system at an earlier time. Pierre-Simon Laplace (1749–1827) was keenly aware of the problem: "… imagine an Intelligence who would know at a given instant of time all forces acting in nature and the position of all things of which the world consists … Then it could derive a result that would embrace in one and the same formula the motion of the largest bodies in the universe and of the lightest atoms. Nothing would be uncertain for this Intelligence." (Chapter B4)

Determinism refers to a system or a process whose future state can in principle be predicted from knowledge of its characteristics at an earlier time. If a system is deterministic, one can in principle predict its future state.

Chaos refers to a (mathematical) system that is deterministic but unpredictable in practice due to its extreme dependence on initial conditions. Mathematicians have explored those points or regions in a multi-dimensional space of parameters that are (potentially) chaotic.

Quantum Uncertainty: One can predict with extremely high accuracy the spatial distribution of photons in a diffraction pattern; however, one can make only a probabilistic statement about the path chosen by a single photon. One can assign a very accurate half-life for decay to a collection of identical radioactive atoms; yet one cannot predict when a single atom will decay.

A related, fundamental constraint is imposed by the Heisenberg uncertainty principle: $\Delta x \cdot \Delta p$ (or $\Delta E \cdot \Delta t$) $> \hbar/2$ is a fundamental physical limitation. As one measures x to ever greater precision, the error, Δx, grows ever smaller; correspondingly, one loses information about p; Δp must grow larger. Planck constant, $h = 6.626 \times 10^{-27}$ erg ($\hbar = h/2\,\Lambda$); $x =$ position; $p =$ momentum; $E =$ energy; $t =$ time.

Randomness of a single coin toss or of a single roll of a dice (die for sticklers) is probabilistic; the distribution of many tosses or of many rolls is highly predictable. That distribution can be described by the binomial distribution (Pascal's triangle) — 1 1 1 1 2 1 1 3 3 1 1 4 6 4 1 — which in the limit is described by the normal distribution (Chapter B2).

Emergence is both a valid and a valuable concept as one addresses more complex systems. To approximation one might consider Weinberger's examples in reverse. Given all the information one might wish about atomic physics, one cannot predict all the structural and reaction characteristics of molecules. Given all the information one might wish about chemistry, one cannot predict all the structural and functional characteristics of proteins or nucleic acids. Given all the information one might wish about bio-macromolecules, one cannot predict all the characteristics of cells. These statements of our limitations continue up to organs, to people, and to societies (Kaufman, 2008). This characterization begs the question of whether an emergent property today will be predictable in the future. Is emergence merely a statement of contemporary ignorance? In practice one wisely uses the concept of maximum parsimony (one of many restatements of what is often referred to as Occam's razor). It is the explanation or interpretation of existing observations or results that involves the fewest (or smallest or most reasonable) assumptions. The most parsimonious interpretation(s) may change, within the existing paradigm (Chapter A11), as new data becomes available.

Vitalism was nominally refuted by Friedrich Wöhler, who synthesized urea, $CO(NH_2)_2$, from ammonium cyanate, NH_4 NCO, in 1828 (Chapter C8). He wrote to Berzelius about "The great tragedy of science, the slaying of a beautiful hypothesis by an ugly fact." No biologist should use the term *vitalism* before age 40 or until having received tenure. Nonetheless, many vital characteristics, such as tissue excitability, might be legitimately described as emergent properties. A single falsification, after Popper, did not in itself spell the doom of vitalism. Whether its demise conforms to Kuhn's formulation of a paradigm shift is problematic.

Francis Crick (Nobel Laureate, 1962) was unequivocal: "And so to those of you who may be vitalists I would make this prophecy: what everyone believed yesterday, and you believe today, only cranks will believe tomorrow." Roger Sperry (Nobel Laureate, 1981) was more sympathetic: "The events of inner experience, as emergent properties of brain processes, become themselves explanatory, causal constructs in their own right, interacting at their own level with their own laws and dynamics. The whole world of inner experience (the world of the humanities) long rejected by 20th century scientific materialism, thus becomes recognized and included within the domain of science." Whether humanists welcome this inclusion is another question.

Ernst Mayr (1904–2005) sought a balance:

> It would be ahistorical to ridicule vitalists. When one reads the writings of one of the leading vitalists like Driesch one is forced to agree with him that many of the basic problems of biology simply cannot be solved by a philosophy as that of Descartes, in which the organism is simply considered a machine … The logic of the critique of the vitalists was impeccable. But all their efforts to find a scientific answer to all the so-called vitalistic phenomena were failures … rejecting the philosophy of reductionism is not an attack on analysis. No complex system can be understood except through careful analysis. However, the interactions of the components must be considered as much as the properties of the isolated components.

Often physicists or ecologists, in the privacy of their own labs or plots, will refer to a device or to a plant as having a will or an urge. One should distinguish a manner of speaking from a deep philosophical commitment.