HISTORY OF SCIENCE

Volume 3

Benjamin Kent

HISTORY OF SCIENCE

VOLUME 3

HISTORY OF SCIENCE

VOLUME 3

Benjamin Kent

BIBLIOTEX
Digital Library

History of Science, Volume 3
by Benjamin Kent

Copyright© 2022 BIBLIOTEX

www.bibliotex.com

All rights reserved. No part of this book may be reproduced or used in any manner without the prior written permission of the copyright owner, except for the use brief quotations in a book review.

To request permissions, contact the publisher at info@bibliotex.com

Ebook ISBN: 9781984668684

Published by:
Bibliotex
Canada
Website: www.bibliotex.com

Contents

Chapter 21

History of Ecology

Ecology is a new science and considered as an important branch of biological science, having only become prominent during the second half of the 20th century. Ecological thought is derivative of established currents in philosophy, particularly from ethics and politics. Its history stems all the way back to the 4th century. One of the first ecologists whose writings survive may have been Aristotle or perhaps his student, Theophrastus, both of whom had interest in many species of animals and plants. Theophrastus described interrelationships between animals and their environment as early as the 4th century BC. Ecology developed substantially in the 18th and 19th century. It began with Carl Linnaeus and his work with the economy of nature. Soon after came Alexander von Humboldt and his work with botanical geography. Alexander von Humboldt and Karl Möbius then contributed with the notion of biocoenosis. Eugenius Warming's work with ecological plant geography led to the founding of ecology as a discipline. Charles Darwin's work also contributed to the science of ecology, and Darwin is often attributed with progressing the discipline more than anyone else in its young history. Ecological thought expanded even more in the early 20th century. Major contributions included: Eduard Suess' and Vladimir Vernadsky's work with the biosphere, Arthur Tansley's ecosystem, Charles Elton's *Animal Ecology*, and Henry Cowles ecological succession. Ecology influenced the social sciences and humanities. Human ecology began in the early 20th century and it recognized humans as an ecological factor. Later James Lovelock advanced views on earth as a macro-organism with the Gaia hypothesis. Conservation stemmed from the science of ecology. Important figures and movements include Shelford and the ESA, National Environmental Policy act, George Perkins Marsh, Theodore Roosevelt, Stephen A. Forbes, and post-Dust Bowl conservation. Later in the 20th century world governments collaborated on man's effects on the biosphere and Earth's environment.

The history of ecology is intertwined with the history of conservation efforts, in particular the founding of the Nature Conservancy.

18th and 19th century Ecological murmurs

Arcadian and Imperial Ecology

In the early Eighteenth century, preceding Carl Linnaeus, two rival schools of thought dominated the growing scientific discipline of ecology. First, Gilbert White a "parson-naturalist" is attributed with developing and endorsing the view of Arcadian ecology. Arcadian ecology advocates for a "simple, humble life for man" and a harmonious relationship with humans and nature. Opposing the Arcadian view is Francis Bacon's ideology, "imperial ecology". Imperialists work "to establish through the exercise of reason and by hard work, man's dominance over nature". Imperial ecologists also believe that man should become a dominant figure over nature and all other organisms as “once enjoyed in the Garden of Eden”. Both views continued their rivalry through the early eighteenth century until Carl Linnaeus's support of imperialism; and in short time due to Linnaeus's popularity, imperial ecology became the dominant view within the discipline.

Carl Linnaeus and Systema Naturae

Carl Linnaeus, a Swedish naturalist, is well known for his work with taxonomy but his ideas helped to lay the groundwork for modern ecology. He developed a two part naming system for classifying plants and animals. Binomial Nomenclature was used to classify, describe, and name different genera and species. The compiled editions of *Systema Naturae* developed and popularized the naming system for plants and animals in modern biology. Reid suggests "Linnaeus can fairly be regarded as the originator of systematic and ecological studies in biodiversity," due to his naming and classifying of thousands of plant and animal species. Linnaeus also influenced the foundations of Darwinian evolution, he believed that there could be change in or between different species within fixed genera. Linnaeus was also one of the first naturalists to place men in the same category as primates.

The botanical geography and Alexander von Humboldt

Throughout the 18th and the beginning of the 19th century, the great maritime powers such as Britain, Spain, and Portugal launched many world exploratory expeditions to develop maritime commerce with other countries, and to discover new natural resources, as well as to catalog them. At the beginning of the 18th century, about twenty thousand plant species were known, versus forty thousand at the beginning of the 19th century, and about 300,000 today.

These expeditions were joined by many scientists, including botanists, such as the German explorer Alexander von Humboldt. Humboldt is often considered as father of ecology. He was the first to take on the study of the relationship between organisms and their environment. He exposed the existing relationships between observed plant species and climate, and described vegetation zones using latitude and altitude, a discipline now known as geobotany. Von Humboldt was accompanied on his expedition by the botanist Aimé Bonpland.

In 1856, the Park Grass Experiment was established at the Rothamsted Experimental Station to test the effect of fertilizers and manures on hay yields. This is the longest-running field experiment in the world.

The notion of biocoenosis: Wallace and Möbius

Alfred Russel Wallace, contemporary and colleague of Darwin, was first to propose a "geography" of animal species. Several authors recognized at the time that species were not independent of each other, and grouped them into plant species, animal species, and later into communities of living beings or biocoenosis. The first use of this term is usually attributed to Karl Möbius in 1877, but already in 1825, the French naturalist Adolphe Dureau de la Malle used the term *societé* about an assemblage of plant individuals of different species.

Warming and the foundation of ecology as discipline

While Darwin focused exclusively on competition as a selective force, Eugen Warming devised a new discipline that took abiotic factors, that is drought, fire, salt, cold etc., as seriously as biotic factors in the assembly of biotic communities. Biogeography before Warming was largely of descriptive nature – faunistic or floristic. Warming's aim was, through the study of organism (plant) morphology and anatomy, i.e. adaptation, to explain why a species occurred under a certain set of environmental conditions. Moreover, the goal of the new discipline was to explain why species occupying similar habitats, experiencing similar hazards, would solve problems in similar ways, despite often being of widely different phylogenetic descent. Based on his personal observations in Brazilian cerrado, in Denmark, Norwegian Finnmark and Greenland, Warming gave the first university course in ecological plant geography. Based on his lectures, he wrote the book ‘Plantesamfund’, which was immediate translated to German, Polish and Russian, later to English as ‘Oecology of Plants’. Through its German edition, the book had an immense effect on British and North American scientists like Arthur Tansley, Henry Chandler Cowles and Frederic Clements.

Malthusian influence

Thomas Robert Malthus was an influential writer on the subject of population and population limits in the early 19th century. His works were very important in shaping the ways in which Darwin saw the world worked. Malthus wrote:

That the increase of population is necessarily limited by the means of subsistence,

That population does invariably increase when the means of subsistence increase, and,

That the superior power of population is repressed, and the actual population kept equal to the means of subsistence, by misery and vice.

In An Essay on the Principle of Population Malthus argues for the reining in of rising population through 2 checks: Positive and Preventive checks. The first raising death rates, the later lowers birthing rates. Malthus also brings forth the idea that the world population will move past the sustainable number of people. This form of thought still continues to influences debates on birth and marriage rates to this theory brought forth by Malthus. The essay had a major influence on Charles Darwin and helped him to theories his theory of Natural Selection. This struggle proposed by Malthusian thought not only influenced the ecological work of Charles Darwin, but helped bring about an economic theory of world of ecology.

Darwinism and the science of ecology

It is often held that the roots of scientific ecology may be traced back to Darwin. This contention may look convincing at first glance inasmuch as *On the Origin of Species* is full of observations and proposed mechanisms that clearly fit within the boundaries of modern ecology (e.g. the cat-to-clover chain – an ecological cascade) and because the term ecology was coined in 1866 by a strong proponent of Darwinism, Ernst Haeckel. However, Darwin never used the word in his writings after this year, not even in his most "ecological" writings such as the foreword to the English edition of Hermann Müller's *The Fertilization of Flowers* (1883) or in his own treatise of earthworms and mull formation in forest soils (The formation of vegetable mould through the action of worms, 1881). Moreover, the pioneers founding ecology as a scientific discipline, such as Eugen Warming, A. F. W. Schimper, Gaston Bonnier, F.A. Forel, S.A. Forbes and Karl Möbius, made almost no reference to Darwin's ideas in their works. This was clearly not out of ignorance or because the works of Darwin were not widespread. Some such as S.A.Forbes studying intricate food webs asked questions as yet unanswered about the instability of food chains that might persist if dominant competitors were not adapted to have self-constraint. Others focused on the dominant themes at the beginning, concern with the relationship between organism morphology and physiology on one side and environment on the other, mainly abiotic environment, hence environmental selection. Darwin's concept of natural selection on the other hand focused primarily on competition. The mechanisms other than competition that he described, primarily the divergence of character which can reduce competition and his statement that "struggle" as he used it was metaphorical and thus included environmental selection, were given less emphasis in the Origin than competition. Despite most portrayals of Darwin conveying him as a non-aggressive recluse who let others fight his battles, Darwin remained all his life a man nearly obsessed with the ideas of competition, struggle and conquest – with all forms of human contact as confrontation.

Although there is nothing incorrect in the details presented in the paragraph above, the fact that Darwinism used a particularly ecological view of adaptation and Haeckel's use and definitions of the term were steeped in Darwinism should not be ignored. According to ecologist and historian Robert P. McIntosh, "the relationship of ecology to Darwinian evolution is explicit in the title of the work in which ecology first appeared."

A more elaborate definition by Haeckel in 1870 is translated on the frontispiece of the influential ecology text known as 'Great Apes' as "... ecology is the study of all those complex interrelations referred to by Darwin as the conditions of the struggle for existence." The issues brought up in the above paragraph are covered in more detail in the Early Beginnings section underneath that of History in the Wikipedia page on Ecology.

Early 20th century ~ Expansion of ecological thought

The biosphere – Eduard Suess and Vladimir Vernadsky

By the 19th century, ecology blossomed due to new discoveries in chemistry by Lavoisier and de Saussure, notably the nitrogen cycle. After observing the fact that life developed only within strict limits of each compartment that makes up the atmosphere, hydrosphere, and lithosphere, the Austrian geologist Eduard Suess proposed the term biosphere in 1875. Suess proposed the name biosphere for the conditions promoting life, such as those found on Earth, which includes flora, fauna, minerals, matter cycles, et cetera.

In the 1920s Vladimir I. Vernadsky, a Russian geologist who had defected to France, detailed the idea of the biosphere in his work "The biosphere" (1926), and described the fundamental principles of the biogeochemical cycles. He thus redefined the biosphere as the sum of all ecosystems.

First ecological damages were reported in the 18th century, as the multiplication of colonies caused deforestation. Since the 19th century, with the industrial revolution, more and more pressing concerns have grown about the impact of human activity on the environment. The term ecologist has been in use since the end of the 19th century.

The ecosystem: Arthur Tansley

Over the 19th century, botanical geography and zoogeography combined to form the basis of biogeography. This science, which deals with habitats of species, seeks to explain the reasons for the presence of certain species in a given location.

It was in 1935 that Arthur Tansley, the British ecologist, coined the term ecosystem, the interactive system established between the biocoenosis (the group of living creatures), and their biotope, the environment in which they live. Ecology thus became the science of ecosystems.

Tansley's concept of the ecosystem was adopted by the energetic and influential biology educator Eugene Odum. Along with his brother, Howard T. Odum, Eugene P. Odum wrote a textbook which (starting in 1953) educated more than one generation of biologists and ecologists in North America.

Ecological succession – Henry Chandler Cowles

At the turn of the 20th century, Henry Chandler Cowles was one of the founders of the emerging study of "dynamic ecology", through his study of ecological succession at the Indiana Dunes, sand dunes at the southern end of Lake Michigan. Here Cowles found evidence of ecological succession in the vegetation and the soil with relation to age. Cowles was very much aware of the roots of the concept and of his (primordial) predecessors. Thus, he attributes the first use of the word to the French naturalist Adolphe Dureau de la Malle, who had described the vegetation development after forest clear-felling, and the first comprehensive study of successional processes to the Finnish botanist Ragnar Hult (1881).

Animal Ecology - Charles Elton

20th century English zoologist and ecologist, Charles Elton, is commonly credited as “the father of animal ecology”. Elton influenced by Victor Shelford's *Animal Communities in Temperate America* began his research on animal ecology as an assistant to his colleague, Julian Huxley, on an ecological survey of the fauna in Spitsbergen in 1921. Elton's most famous studies were conducted during his time as a biological consultant to the Hudson Bay Company to help understand the fluctuations in the company's fur harvests. Elton studied the population fluctuations and dynamics of snowshoe hare, Canadian lynx, and other mammals of the region. Elton is also considered the first to coin the terms, food chain and food cycle in his famous book *Animal Ecology*. Elton is also attributed with contributing to disciplines of: invasion ecology, community ecology, and wildlife disease ecology.

G. Evelyn Hutchinson - father of modern ecology

George “G” Evelyn Hutchinson was a 20th-century ecologist who is commonly recognized as the “Father of Modern Ecology”. Hutchinson is of English descent but spent most of professional career studying in New Haven, Connecticut at Yale University. Throughout his career, over six decades, Hutchinson contributed to the sciences of limnology, entomology, genetics, biogeochemistry, mathematical theory of population dynamics and many more. Hutchinson is also attributed as being the first to infuse science with theory within the discipline of ecology. Hutchinson was also one of the first credited with combining ecology with mathematics. Another major contribution of Hutchinson was his development of the current definition of an organism's "niche" – as he recognized the role of an organism within its community. Finally, along with his great impact within the discipline of ecology throughout his professional years, Hutchinson also left a lasting impact in ecology through his many students he inspired. Foremost among them were Robert H. MacArthur, who received his PhD under Hutchinson, and Raymond L. Lindemann, who finished his PhD dissertation during a fellowship under him. MacArthur became the leader of theoretical ecology and, with E. O. Wilson, developed island biography theory. Raymond Lindemann was instrumental in the development of modern ecosystem science.

20th century transition to modern ecology

"What is ecology?" was a questioned that was asked in almost every decade of the 20th century. Unfortunately, the answer most often was that it was mainly a point of view to be used in other areas of biology and also "soft," like sociology, for example, rather than "hard," like physics. Although autecology (essentially physiological ecology) could progress through the typical scientific method of observation and hypothesis testing, synecology (the study of animal and plant communities) and genecology (evolutionary ecology), for which experimentation was as limited as it was for, say, geology, continued with much the same inductive gathering of data as did natural history studies. Most often, patterns, present and historical, were used to develop theories having explanatory power, but which had little actual data in support. Darwin's theory, as much as it is a foundation of modern biology, is a prime example.

G. E. Hutchinson, identified above as the “father of modern ecology,” through his influence raised the status of much of ecology to that of a rigorous science. By shepherding of Raymond Lindemann's work on the trophic-dynamic concept of ecosystems through the publication process after Lindemann's untimely death, Hutchinson set the groundwork for what became modern ecosystem science. With his two famous papers in the late1950s, “Closing remarks,” and “Homage to Santa Rosalia,” as they are now known, Hutchinson launched the theoretical ecology which Robert MacArthur championed.

Ecosystem science became rapidly and sensibly associated with the “Big Science”—and obviously “hard” science—of atomic testing and nuclear energy. It was brought in by Stanley Auerbach, who established the Environmental Sciences Division at Oak Ridge National Laboratory, to trace the routes of radionulcides through the environment, and by the Odum brothers, Howard and Eugene, much of whose early work was supported by the Atomic Energy Commission. Eugene Odum's textbook, *Fundamentals of Ecology*, has become something of a bible today. When, in the 1960s, the International Biological Program (IBP) took on an ecosystem character, ecology, with its foundation in systems science, forever entered the realm of Big

Science, with projects having large scopes and big budgets. Just two years after the publication of *Silent Spring* in 1962, ecosystem ecology was trumpeted as THE science of the environment in a series of articles in a special edition of *BioScience*.

Theoretical ecology took a different path to established its legitimacy, especially at eastern universities and certain West Coast campuses. It was the path of Robert MacArthur, who used simple mathematics in his "Three Influential Papers, also published in the late 1950s, on population and community ecology. Although the simple equations of theoretical ecology at the time, were unsupported by data, they still were still deemed to be "heuristic." They were resisted by a number of traditional ecologists, however, whose complaints of "intellectual censorship" of studies that did not fit into the hypothetico-deductive structure of the new ecology might be seen as evidence of the stature to which the Hutchinson-MacArthur approach had risen by the 1970s.

MacArthur's untimely death in 1972 was also about the time that postmodernism and the "Science Wars" came to ecology. The names of Kuhn, Wittgenstein, Popper, Lakatos, and Feyerbrend began to enter into arguments in the ecological literature. Darwin's theory of adaptation through natural selection was accused of being tautological. Questions were raised over whether ecosystems were cybernetic and whether ecosystem theory was of any use in application to environmental management. Most vituperative of all was the debate that arose over MacArthur-style ecology.

Matters came to a head after a symposium organized by acolytes of MacArthur in homage to him and a second symposium organized by what was disparagingly called the "Tallahassee Mafia" at Wakulla Springs in Florida. The homage volume, published in 1975, had an extensive chapter written by Jared Diamond, who at the time taught kidney physiology at the UCLA School of Medicine, that presented a series of "assembly rules" to explain the patterns of bird species found on island archipelagos, such as Darwin's famous finches on the Galapagos Islands. The Wakulla conference was organized by a group of dissenters led by Daniel Simberloff and Donald Strong, Jr., who were described by David Quammen in his book as arguing that those patterns "might be nothing more than the faces we see in the moon, in clouds, in Rorschach inkblots." Their point was that Diamond's work (and that of others) did not fall within the criterion of falsifiability, laid down for science by the philosopher, Karl Popper. A reviewer of the exchanges between the two camps in an issue of *Synthese* found "images of hand-to-hand combat or a bar-room brawl" coming to mind. The Florida State group suggested a method that they developed, that of "null" models, to be used much in the way that all scientists use null hypotheses to verify that their results might not have been obtained merely by chance. It was most sharply rebuked by Diamond and Michel Gilpin in the symposium volume and Jonathan Roughgarden in the American Naturalist.

There was a parallel controversy adding heat to above that became known in conservation circles as SLOSS (Single Large or Several Small reserves). Diamond had also proposed that, according to the theory of island geography developed by MacArthur and E. O. Wilson, nature preserves should be designed to be as large as possible and maintained as a unified entity. Even cutting a road through a natural area, in Diamond's interpretation of MacArthur and Wilson's theory, would lead to the loss of species, due to the smaller areas of the remaining pieces. Simberloff, meanwhile, who had defaunated mangrove islands off the Florida coast in his award-winning experimental study under E. O. Wilson and tested the fit of the species-area curve of island biogeography theory to the fauna that returned, had gathered data that showed quite the opposite: that many smaller fragments together sometimes held more species that the original whole. It led to considerable vituperation on the pages of *Science*.

In the end, in a somewhat Kuhnian fashion, the arguments probably will finally be settled (or not) by the passing of the participants. However, ecology continues apace as a rigorous, even experimental science. Null models, admittedly difficult to perfect, are in use, and, although a leading conservation scientist recently lauded island biogeography theory as “one of the most elegant and important theories in contemporary ecology, towering above thousands of lesser ideas and concept,” he nevertheless finds that “the species-area curve is a blunt tool in many contexts” and “now seems simplistic to the point of being cartoonish.”

Ecological Influence on the Social Sciences and Humanities

Human ecology

Human ecology began in the 1920s, through the study of changes in vegetation succession in the city of Chicago. It became a distinct field of study in the 1970s. This marked the first recognition that humans, who had colonized all of the Earth's continents, were a major ecological factor. Humans greatly modify the environment through the development of the habitat (in particular urban planning), by intensive exploitation activities such as logging and fishing, and as side effects of agriculture, mining, and industry. Besides ecology and biology, this discipline involved many other natural and social sciences, such as anthropology and ethnology, economics, demography, architecture and urban planning, medicine and psychology, and many more. The development of human ecology led to the increasing role of ecological science in the design and management of cities.

In recent years human ecology has been a topic that has interested organizational researchers. Hannan and Freeman (*Population Ecology of Organizations (1977)*, American Journal of Sociology) argue that organizations do not only adapt to an environment. Instead it is also the environment that selects or rejects populations of organizations. In any given environment (in equilibrium) there will only be one form of organization (isomorphism). Organizational ecology has been a prominent theory in accounting for diversities of organizations and their changing composition over time.

James Lovelock and the Gaia hypothesis

The Gaia theory, proposed by James Lovelock, in his work *Gaia: A New Look at Life on Earth*, advanced the view that the Earth should be regarded as a single living macro-organism. In particular, it argued that the ensemble of living organisms has jointly evolved an ability to control the global environment — by influencing major physical parameters as the composition of the atmosphere, the evaporation rate, the chemistry of soils and oceans — so as to maintain conditions favorable to life. The idea has been supported by Lynn Margulis who extended her endosymbiotic theory which suggests that cell organelles originated from free living organisms to the idea that individual organisms of many species could be considered as symbionts within a larger metaphorical "super-organism".

This vision was largely a sign of the times, in particular the growing perception after the Second World War that human activities such as nuclear energy, industrialization, pollution, and overexploitation of natural resources, fueled by exponential population growth, were threatening to create catastrophes on a planetary scale, and has influenced many in the environmental movement since then.

History and relationship between ecology and conservation and environmental movements

Environmentalists and other conservationists have used ecology and other sciences (e.g., climatology) to support their advocacy positions. Environmentalist views are often controversial for political or economic reasons. As a result, some scientific work in ecology directly influences policy and political debate; these in turn often direct ecological research.

The history of ecology, however, should not be conflated with that of environmental thought. Ecology as a modern science traces only from Darwin's publication of Origin of Species and Haeckel's subsequent naming of the science needed to study Darwin's theory. Awareness of humankind's effect on its environment has been traced to Gilbert White in 18th-century Selborne, England. Awareness of nature and its interactions can be traced back even farther in time. Ecology before Darwin, however, is analogous to medicine prior to Pasteur's discovery of the infectious nature of disease. The history is there, but it is only partly relevant.

Neither Darwin nor Haeckel, it is true, did self-avowed ecological studies. The same can be said for researchers in a number of fields who contributed to ecological thought well into the 1940s without avowedly being ecologists. Raymond Pearl's population studies are a case in point. Ecology in subject matter and techniques grew out of studies by botanists and plant geographers in the late 19th and early 20th centuries that paradoxically lacked Darwinian evolutionary perspectives. Until Mendel's studies with peas were rediscovered and melded into the Modern Synthesis, Darwinism suffered in credibility. Many early plant ecologists had a Lamarckian view of inheritance, as did Darwin, at times. Ecological studies of animals and plants, preferably live and in the field, continued apace however.

Conservation and environmental movements - 20th Century

When the Ecological Society of America (ESA) was chartered in 1915, it already had a conservation perspective. Victor E. Shelford, a leader in the society's formation, had as one of its goals the preservation of the natural areas that were then the objects of study by ecologists, but were in danger of being degraded by human incursion. Human ecology had also been a visible part of the ESA at its inception, as evident by publications such as: "The Control of Pneumonia and Influenza by the Weather," "An Overlook of the Relations of Dust to Humanity," "The Ecological Relations of the Polar Eskimo," and "City Street Dust and Infectious Diseases," in early pages of Ecology and Ecological Monographs. The ESA's second president, Ellsworth Huntington, was a human ecologist. Stephen Forbes, another early president, called for "humanizing" ecology in 1921, since man was clearly the dominant species on the Earth.

This auspicious start actually was the first of a series of fitful progressions and reversions by the new science with regard to conservation. Human ecology necessarily focused on man-influenced environments and their practical problems. Ecologists in general, however, were trying to establish ecology as a basic science, one with enough prestige to make inroads into Ivy League faculties. Disturbed environments, it was thought, would not reveal nature's secrets.

Interest in the environment created by the American Dust Bowl produced a flurry of calls in 1935 for ecology to take a look at practical issues. Pioneering ecologist C. C. Adams wanted to return human ecology to the science. Frederic E. Clements, the dominant plant ecologist of the day, reviewed land use issues leading to the Dust Bowl in terms of his ideas on plant succession and climax. Paul Sears reached a wide audience with his book, *Deserts on the March*. World War II, perhaps, caused the issue to be put aside.

The tension between pure ecology, seeking to understand and explain, and applied ecology, seeking to describe and repair, came to a head after World War II. Adams again tried to push the ESA into applied areas by having it raise an endowment to promote ecology. He predicted that "a great expansion of ecology" was imminent "because of its integrating tendency." Ecologists, however, were sensitive to the perception that ecology was still not considered a rigorous, quantitative science. Those who pushed for applied studies and active involvement in conservation were once more discreetly rebuffed. Human ecology became subsumed by sociology. It was sociologist Lewis Mumford who brought the ideas of George Perkins Marsh to modern attention in the 1955 conference, "Man’s Role in Changing the Face of the Earth." That prestigious conclave was dominated by social scientists. At it, ecology was accused of "lacking experimental methods" and neglecting "man as an ecological agent." One participant dismissed ecology as "archaic and sterile." Within the ESA, a frustrated Shelford started the Ecologists' Union when his Committee on Preservation of Natural Conditions ceased to function due to the political infighting over the ESA stance on conservation. In 1950, the fledgling organization was renamed and incorporated as the Nature Conservancy, a name borrowed from the British government agency for the same purpose.

Two events, however, brought ecology's course back to applied problems. One was the Manhattan Project. It had become the Nuclear Energy Commission after the war. It is now the Department of Energy (DOE). Its ample budget included studies of the impacts of nuclear weapon use and production. That brought ecology to the issue, and it made a "Big Science" of it. Ecosystem science, both basic and applied, began to compete with theoretical ecology (then called evolutionary ecology and also mathematical ecology). Eugene Odum, who published a very popular ecology textbook in 1953, became the champion of the ecosystem. In his publications, Odum called for ecology to have an ecosystem and applied focus.

The second event was the publication of Silent Spring. Rachel Carson's book brought ecology as a word and concept to the public. Her influence was instant. A study committee, prodded by the publication of the book, reported to the ESA that their science was not ready to take on the responsibility being given to it.

Carson's concept of ecology was very much that of Gene Odum. As a result, ecosystem science dominated the International Biological Program of the 1960s and 1970s, bringing both money and prestige to ecology. Silent Spring was also the impetus for the environmental protection programs that were started in the Kennedy and Johnson administrations and passed into law just before the first Earth Day. Ecologists' input was welcomed. Former ESA President Stanley Cain, for example, was appointed an Assistant Secretary in the Department of the Interior.

The environmental assessment requirement of the 1969 National Environmental Policy Act (NEPA), "legitimized ecology," in the words of one environmental lawyer. An ESA President called it "an ecological 'Magna Carta.'" A prominent Canadian ecologist declared it a "boondoggle." NEPA and similar state statutes, if nothing else, provided much employment for ecologists. Therein was the issue. Neither ecology nor ecologists were ready for the task. Not enough ecologists were available to work on impact assessment, outside of the DOE laboratories, leading to the rise of "instant ecologists," having dubious credentials and capabilities. Calls began to arise for the professionalization of ecology. Maverick scientist Frank Egler, in particular, devoted his sharp prose to the task. Again, a schism arose between basic and applied scientists in the ESA, this time exacerbated by the question of environmental advocacy. The controversy, whose history has yet to receive adequate treatment, lasted through the 1970s and 1980s, ending with a voluntary certification process by the ESA, along with lobbying arm in Washington.

Post-Earth Day, besides questions of advocacy and professionalism, ecology also had to deal with questions having to do with its basic principles. Many of the theoretical principles and methods of both ecosystem science and evolutionary ecology began to show little value in environmental analysis and assessment. Ecologist, in general, started to question the methods and logic of their science under the pressure of its new notoriety. Meanwhile, personnel with government agencies and environmental advocacy groups were accused of religiously applying dubious principles in their conservation work. Management of endangered Spotted Owl populations brought the controversy to a head.

Conservation for ecologists created travails paralleling those nuclear power gave former Manhattan Project scientists. In each case, science had to be reconciled with individual politics, religious beliefs, and worldviews, a difficult process. Some ecologists managed to keep their science separate from their advocacy; others unrepentantly became avowed environmentalists.

Roosevelt & American conservation

Theodore Roosevelt was interested in nature from a young age. He carried his passion for nature into his political policies. Roosevelt felt it was necessary to preserve the resources of the nation and its environment. In 1902 he created the federal reclamation service, which reclaimed land for agriculture. He also created the Bureau of Forestry. This organization, headed by Gifford Pinchot, was formed to manage and maintain the nations timberlands. Roosevelt signed the Act for the Preservation of American Antiquities in 1906. This act allowed for him to "declare by public proclamation historic landmarks, historic and prehistoric structures, and other objects of historic and scientific interest that are situated upon lands owned or controlled by the Government of the United States to be national monuments." Under this act he created up to 18 national monuments. During his presidency, Roosevelt established 51 Federal Bird Reservations, 4 National Game Preserves, 150 National Forests, and 5 National Parks. Overall he protected over 200 million acres of land.

Ecology and global policy

Ecology became a central part of the World's politics as early as 1971, UNESCO launched a research program called *Man and Biosphere*, with the objective of increasing knowledge about the mutual relationship between humans and nature. A few years later it defined the concept of Biosphere Reserve.

In 1972, the United Nations held the first international Conference on the Human Environment in Stockholm, prepared by Rene Dubos and other experts. This conference was the origin of the phrase "Think Globally, Act Locally". The next major events in ecology were the development of the concept of biosphere and the appearance of terms "biological diversity"—or now more commonly biodiversity—in the 1980s. These terms were developed during the Earth Summit in Rio de Janeiro in 1992, where the concept of the biosphere was recognized by the major international organizations, and risks associated with reductions in biodiversity were publicly acknowledged.

Then, in 1997, the dangers the biosphere was facing were recognized all over the world at the conference leading to the Kyoto Protocol. In particular, this conference highlighted the increasing dangers of the greenhouse effect – related to the increasing concentration of greenhouse gases in the atmosphere, leading to global changes in climate. In Kyoto, most of the world's nations recognized the importance of looking at ecology from a global point of view, on a worldwide scale, and to take into account the impact of humans on the Earth's environment.

Chapter 22

History of Geography

The **history of geography** includes many histories of geography which have differed over time and between different cultural and political groups. In more recent developments, geography has become a distinct academic discipline. 'Geography' derives from the Greek γεωγραφία – *geographia*, literally "Earth-writing", that is, description or writing about the Earth. The first person to use the word *geographia* was Eratosthenes (276–194 BC). However, there is evidence for recognizable practices of geography, such as cartography (map-making), prior to the use of the term.

Egypt

The known world of Ancient Egypt saw the Nile as the centre, and the world as based upon "the" river. Various oases were known to the east and west, and were considered locations of various gods (e.g. Siwa, for Amon)12 . To the South lay the Kushitic region, known as far as the 4th cataract. Punt was a region south along the shores of the Red Sea. Various Asiatic peoples were known as Retenu, Kanaan, Que, Harranu, or Khatti (Hittites). At various times especially in the Late Bronze Age Egyptians had diplomatic and trade relationships with Babylonia and Elam. The Mediterranean was called "the Great Green" and was believed to be part of a world encircling ocean. Europe was unknown although may have become part of the Egyptian world view in Phoenician times. To the west of Asia lay the realms of Keftiu, possibly Crete, and Mycenae (thought to be part of a chain of islands, that joined Cyprus, Crete, Sicily and later perhaps Sardinia, Corsica and the Balarics to Africa).

Babylon

The oldest known world maps date back to ancient Babylon from the 9th century BC. The best known Babylonian world map, however, is the *Imago Mundi* of 600 BC. The map as reconstructed by Eckhard Unger shows Babylon on the Euphrates, surrounded by a circular landmass showing Assyria, Urartu and several cities, in turn surrounded by a "bitter river" (Oceanus), with seven islands arranged around it so as to form a seven-pointed star. The accompanying text mentions seven outer regions beyond the encircling ocean. The descriptions of five of them have survived.

In contrast to the *Imago Mundi*, an earlier Babylonian world map dating back to the 9th century BC depicted Babylon as being further north from the center of the world, though it is not certain what that center was supposed to represent.

Greco-Roman world

The ancient Greeks view Homer as the founder of geography. His works the *Iliad* and the *Odyssey* are works of literature, but both contain a great deal of geographical information. Homer describes a circular world ringed by a single massive ocean. The works show that the Greeks by the 8th century BC had considerable knowledge of the geography of the eastern Mediterranean. The poems contain a large number of place names and descriptions, but for many of these it is uncertain what real location, if any, is actually being referred to.

Thales of Miletus is one of the first known philosophers known to have wondered about the shape of the world. He proposed that the world was based on water, and that all things grew out of it. He also laid down many of the astronomical and mathematical rules that would allow geography to be studied scientifically. His successor Anaximander is the first person known to have attempted to create a scale map of the known world and to have introduced the gnomon to Ancient Greece.

Hecataeus of Miletus initiated a different form of geography, avoiding the mathematical calculations of Thales and Anaximander he learnt about the world by gathering previous works and speaking to the sailors who came through the busy port of Miletus. From these accounts he wrote a detailed prose account of what was known of the world. A similar work, and one that mostly survives today, is Herodotus' *Histories*. While primarily a work of history, the book contains a wealth of geographic descriptions covering much of the known world. Egypt, Scythia, Persia, and Asia Minor are all described, including a mention of India. The description of Africa as a whole are contentious, with Herodotus describing the land surrounded by a sea. Though he described the Phoenicians as having circumnavigated Africa in the 6th century BC, through much of later European history the Indian Ocean was thought to be an inland sea, the southern part of Africa wrapping around in the south to connect with the eastern part of Asia. This was not completely abandoned by Western cartographers until the circumnavigation of Africa by Vasco da Gama. Some, though, hold that the descriptions of areas such as India are mostly imaginary. Regardless, Herodotus made important observations about geography. He is the first to have noted the process by which large rivers, such as the Nile, build up deltas, and is also the first recorded as observing that winds tend to blow from colder regions to warmer ones.

Pythagoras was perhaps the first to propose a spherical world, arguing that the sphere was the most perfect form. This idea was embraced by Plato, and Aristotle presented empirical evidence to verify this. He noted that the Earth's shadow during a lunar eclipse is curved from any angle (near the horizon or high in the sky), and also that stars increase in height as one moves north. Eudoxus of Cnidus used the idea of a sphere to explain how the sun created differing climatic zones based on latitude. This led the Greeks to believe in a division of the world into five regions. At each of the poles was an uncharitably cold region. While extrapolating from the heat of the Sahara it was deduced that the area around the equator was unbearably hot. Between these extreme regions both the northern and southern hemispheres had a temperate belt suitable for human habitation.

Hellenistic period

These theories clashed with the evidence of explorers, however, Hanno the Navigator had traveled as far south as Sierra Leone, and Egyptian Pharaoh Necho II of Africa is related by Herodotus and others as having commissioned a successful circumnavigation of Africa by Phoenician sailors. While they were sailing west around the Southern tip of Africa, it was found that the sun was to their right (the north). This is thought to have been a key trigger in the realization that the earth is spherical, in the classical world.

In the 4th century BC the Greek explorer Pytheas traveled through northeast Europe, and circled the British Isles. He found that the region was considerably more habitable than theory expected, but his discoveries were largely dismissed by his contemporaries because of this. Conquerors also carried out exploration, for example, Caesar's invasions of Britain and Germany, expeditions/invasions sent by Augustus to Arabia Felix and Ethiopia (*Res Gestae* 26), and perhaps the greatest Ancient Greek explorer of all, Alexander the Great, who deliberately set out to learn more about the east through his military expeditions and so took a large number of geographers and writers with his army who recorded their observations as they moved east.

The ancient Greeks divided the world into three continents, Europe, Asia, and Libya (Africa). The Hellespont formed the border between Europe and Asia. The border between Asia and Libya was generally considered to be the Nile river, but some geographers, such as Herodotus objected to this. Herodotus argued that there was no difference between the people on the east and west sides of the Nile, and that the Red Sea was a better border. The relatively narrow habitable band was considered to run from the Atlantic Ocean in the west to an unknown sea somewhere east of India in the east. The southern portion of Africa was unknown, as was the northern portion of Europe and Asia, so it was believed that they were circled by a sea. These areas were generally considered uninhabitable.

The size of the Earth was an important question to the Ancient Greeks. Eratosthenes calculated the Earth's circumference with great precision. Since the distance from the Atlantic to India was roughly known, this raised the important question of what was in the vast region east of Asia and to the west of Europe. Crates of Mallus proposed that there were in fact four inhabitable land masses, two in each hemisphere. In Rome a large globe was created depicting this world. Posidonius set out to get a measurement, but his number actually was considerably smaller than the real one, yet it became accepted that the eastern part of Asia was not a huge distance from Europe.

Roman period

While the works of almost all earlier geographers have been lost, many of them are partially known through quotations found in Strabo (64/63 BC – ca. AD 24). Strabo's seventeen volume work of geography is almost completely extant, and is one of the most important sources of information on classical geography. Strabo accepted the narrow band of habitation theory, and rejected the accounts of Hanno and Pytheas as fables. None of Strabo's maps survive, but his detailed descriptions give a clear picture of the status of geographical knowledge of the time. Pliny the Elder's (AD 23 – 79) *Natural History* also has sections on geography. A century after Strabo Ptolemy (AD 90 – 168) launched a similar undertaking. By this time the Roman Empire had expanded through much of Europe, and previously unknown areas such as the British Isles had been explored. The Silk Road was also in operation, and for the first time knowledge of the far east began to be known. Ptolemy's *Geographia* opens with a theoretical discussion about the nature and techniques of geographical inquiry, and then moves to detailed descriptions of much the known world. Ptolemy lists a huge number of cities, tribes, and sites and places them in the world. It is uncertain what Ptolemy's names correspond to in the modern world, and a vast amount of scholarship has gone into trying to link Ptolemaic descriptions to known locations.

It was the Romans who made far more extensive practical use of geography and maps. The Roman transportation system, consisting of 55,000 miles of roads, could not have been designed without the use of geographical systems of measurement and triangulation. The *cursus publicus*, a department of the Roman government devoted to transportation, employed full-time *gromatici* (surveyors). The surveyors' job was to gather topographical information and then to determine the straightest possible route where a road might be built. Instruments and principles used included sun dials for determining direction, theodolites for measuring horizontal angles, and triangulation without which the creation of perfectly straight stretches, some as long as 35 miles, would have been impossible. During the Greco-Roman era, those who performed geographical work could be divided into four categories:

- Land surveyors determined the exact dimensions of a particular area such as a field, dividing the land into plots for distribution, or laying out the streets in a town.
- Cartographical surveyors made maps, involving finding latitudes, longitudes and elevations.

- Military surveyors were called upon to determine such information as the width of a river an army would need to cross.
- Engineering surveyors investigated terrain in order to prepare the way for roads, canals, aqueducts, tunnels and mines.

Around AD 400 a scroll map called the Peutinger Table was made of the known world, featuring the Roman road network. Besides the Roman Empire which at that time spanned from Britain to the Middle East and Africa, the map includes India, Sri Lanka and China. Cities are demarcated using hundreds of symbols. It measures 1.12 ft high and 22.15 ft long. The tools and principles of geography used by the Romans would be closely followed with little practical improvement for the next 700 years.

India

A vast corpus of Indian texts embraced the study of geography. The Vedas and Puranas contain elaborate descriptions of rivers and mountains and treat the relationship between physical and human elements. According to religious scholar Diana Eck, a notable feature of geography in India is its interweaving with Hindu mythology,

No matter where one goes in India, one will find a landscape in which mountains, rivers, forests, and villages are elaborately linked to the stories and gods of Indian culture. Every place in this vast country has its story; and conversely, every story of Hindu myth and legend has its place.

Ancient period

The geographers of ancient India put forward theories regarding the origin of the earth. They theorized that the earth was formed by the solidification of gaseous matter and that the earth's crust is composed of hard rocks (sila), clay (bhumih) and sand (asma). Theories were also propounded to explain earthquakes (bhukamp) and it was assumed that earth, air and water combined to cause earthquakes. The Arthashastra, a compendium by Kautilya (also known as Chanakya) contains a range of geographical and statistical information about the various regions of India. The composers of the Puranas divided the known world into seven continents of dwipas, Jambu Dwipa, Krauncha Dwipa, Kusha Dwipa, Plaksha Dwipa, Pushkara Dwipa, Shaka Dwipa and Shalmali Dwipa. Descriptions were provided for the climate and geography of each of the dwipas.

Early Medieval period

The Vishnudharmottara Purana (compiled between 300 and 350 AD) contains six chapters on physical and human geography. The locational attributes of peoples and places, and various seasons are the topics of these chapters. Varahamihira's Brihat-Samhita gave a thorough treatment of planetary movements, rainfall, clouds and the formation of water. The mathematician-astronomer Aryabhata gave a precise estimate of the earth's circumference in his treatise Āryabhaṭīya. Aryabhata accurately calculated the Earth's circumference as 24,835 miles, which was only 0.2% smaller than the actual value of 24,902 miles.

Late Medieval period

The Mughal chronicles Tuzuk-i-Jehangiri, Ain-i-Akbari and Dastur-ul-aml contain detailed geographical narratives. These were based on the earlier geographical works of India and the advances made by medieval Muslim geographers, particularly the work of Alberuni.

China

In China, the earliest known geographical Chinese writing dates back to the 5th century BC, during the beginning of the Warring States period (481 BC – 221 BC). This work was the *Yu Gong* ('Tribute of Yu') chapter of the *Shu Jing* or *Book of Documents*, which describes the traditional nine provinces of ancient China, their kinds of soil, their characteristic products and economic goods, their tributary goods, their trades and vocations, their state revenues and agricultural systems, and the various rivers and lakes listed and placed accordingly. The nine provinces at the time of this geographical work were relatively small in size compared to those of modern China with the book's descriptions pertaining to areas of the Yellow River, the lower valleys of the Yangtze and the plain between them as well as the Shandong peninsula and to the west the most northern parts of the Wei and Han Rivers along with the southern parts of modern-day Shanxi province.

In this ancient geographical treatise, which would greatly influence later Chinese geographers and cartographers, the Chinese used the mythological figure of Yu the Great to describe the known earth (of the Chinese). Apart from the appearance of Yu, however, the work was devoid of magic, fantasy, Chinese folklore, or legend. Although the Chinese geographical writing in the time of Herodotus and Strabo were of lesser quality and contained less systematic approach, this would change from the 3rd century onwards, as Chinese methods of documenting geography became more complex than those found in Europe, a state of affairs that would persist until the 13th century.

The earliest extant maps found in archeological sites of China date to the 4th century BC and were made in the ancient State of Qin. The earliest known reference to the application of a geometric grid and mathematically graduated scale to a map was contained in the writings of the cartographer Pei Xiu (224–271). From the 1st century AD onwards, official Chinese historical texts contained a geographical section, which was often an enormous compilation of changes in place-names and local administrative divisions controlled by the ruling dynasty, descriptions of mountain ranges, river systems, taxable products, etc. The ancient Chinese historian Ban Gu (32–92) most likely started the trend of the gazetteer in China, which became prominent in the Northern and Southern dynasties period and Sui dynasty. Local gazetteers would feature a wealth of geographic information, although its cartographic aspects were not as highly professional as the maps created by professional cartographers.

From the time of the 5th century BC *Shu Jing* forward, Chinese geographical writing provided more concrete information and less legendary element. This example can be seen in the 4th chapter of the *Huainanzi* (Book of the Master of Huainan), compiled under the editorship of Prince Liu An in 139 BC during the Han dynasty (202 BC – 202 AD). The chapter gave general descriptions of topography in a systematic fashion, given visual aids by the use of maps (di tu) due to the efforts of Liu An and his associate Zuo Wu. In Chang Chu's *Hua Yang Guo Chi* (*Historical Geography of Szechuan*) of 347, not only rivers, trade routes, and various tribes were described, but it also wrote of a 'Ba Jun Tu Jing' ('Map of Szechuan'), which had been made much earlier in 150. The *Shui Jing* (*Waterways Classic*) was written anonymously in the 3rd century during the Three Kingdoms era (attributed often to Guo Pu), and gave a description of some 137 rivers found throughout China. In the 6th century, the book was expanded to forty times its original size by the geographers Li Daoyuan, given the new title of *Shui Jing Zhu* (*The Waterways Classic Commented*).

In later periods of the Song dynasty (960–1279) and Ming dynasty (1368–1644), there were much more systematic and professional approaches to geographic literature. The Song dynasty poet, scholar, and government official Fan Chengda (1126–1193) wrote the geographical treatise known as the *Gui Hai Yu Heng Chi*. It focused primarily on the topography of the land, along with the agricultural, economic and commercial products of each region in China's southern provinces. The polymath Chinese scientist Shen Kuo (1031–1095) devoted a significant amount of his written work to geography, as well as a hypothesis of land formation (geomorphology) due to the evidence of marine fossils found far inland, along with bamboo fossils found underground in a region far from where bamboo was suitable to grow. The 14th-century Yuan dynasty geographer Na-xin wrote a treatise of archeological topography of all the regions north of the Yellow River, in his book *He Shuo Fang Gu Ji*. The Ming dynasty geographer Xu Xiake

(1587–1641) traveled throughout the provinces of China (often on foot) to write his enormous geographical and topographical treatise, documenting various details of his travels, such as the locations of small gorges, or mineral beds such as mica schists. Xu's work was largely systematic, providing accurate details of measurement, and his work (translated later by Ding Wenjiang) read more like a 20th-century field surveyor than an early 17th-century scholar.

The Chinese were also concerned with documenting geographical information of foreign regions far outside of China. Although Chinese had been writing of civilizations of the Middle East, India, and Central Asia since the traveler Zhang Qian (2nd century BC), later Chinese would provide more concrete and valid information on the topography and geographical aspects of foreign regions. The Tang dynasty (618–907) Chinese diplomat Wang Xuance traveled to Magadha (modern northeastern India) during the 7th century. Afterwards he wrote the book *Zhang Tian-zhu Guo Tu* (Illustrated Accounts of Central India), which included a wealth of geographical information. Chinese geographers such as Jia Dan (730–805) wrote accurate descriptions of places far abroad. In his work written between 785 and 805, he described the sea route going into the mouth of the Persian Gulf, and that the medieval Iranians (whom he called the people of the Luo-He-Yi country, i.e. Persia) had erected 'ornamental pillars' in the sea that acted as lighthouse beacons for ships that might go astray. Confirming Jia's reports about lighthouses in the Persian Gulf, Arabic writers a century after Jia wrote of the same structures, writers such as al-Mas'udi and al-Muqaddasi. The later Song dynasty ambassador Xu Jing wrote his accounts of voyage and travel throughout Korea in his work of 1124, the

Xuan-He Feng Shi Gao Li Tu Jing (*Illustrated Record of an Embassy to Korea in the Xuan-He Reign Period*). The geography of medieval Cambodia (the Khmer Empire) was documented in the book *Zhen-La Feng Tu Ji* of 1297, written by Zhou Daguan.

Middle Ages

Byzantine Empire and Syria

After the fall of the western Roman Empire, the Eastern Roman Empire, ruled from Constantinople and known as the Byzantine Empire, continued to thrive and produced several noteworthy geographers. Stephanus of Byzantium (6th century) was a grammarian at Constantinople and authored the important geographical dictionary *Ethnica*. This work is of enormous value, providing well-referenced geographical and other information about ancient Greece.

The geographer Hierocles (6th century) authored the *Synecdemus* (prior to AD 535) in which he provides a table of administrative divisions of the Byzantine Empire and lists the cities in each. The *Synecdemus* and the *Ethnica* were the principal sources of Constantine VII's work on the Themes or divisions of Byzantium, and are the primary sources we have today on political geography of the sixth-century East.

George of Cyprus is known for his *Descriptio orbis Romani(Description of the Roman world)*, written in the decade 600–610. Beginning with Italy and progressing counterclockwise including Africa, Egypt and the western Middle East, George lists cities, towns, fortresses and administrative divisions of the Byzantine or Eastern Roman Empire.

Cosmas Indicopleustes, (6th century) also known as "Cosmas the Monk," was an Alexandrian merchant. By the records of his travels, he seems to have visited India, Sri Lanka, the Kingdom of Axum in modern Ethiopia, and Eritrea. Included in his work *Christian Topography* were some of the earliest world maps. Though Cosmas believed the earth to be flat, most Christian geographers of his time disagreed with him.

Syrian bishop Jacob of Edessa (633–708) adapted scientific material sourced from Aristotle, Theophrastus, Ptolemy and Basil to develop a carefully structured picture of the cosmos. He corrects his sources and writes more scientifically, whereas Basil's *Hexaemeron* is theological in style.

Karl Müller has collected and printed several anonymous works of geography from this era, including the *Expositio totius mundi.*

Islamic world

- Main article: Geography and cartography in medieval Islam

In the latter 7th century, adherents of the new religion of Islam surged northward out of Arabia taking over lands in which Jews, Byzantine Christians and Persian Zoroastrians had been established for centuries. There, carefully preserved in the monasteries and libraries, they discovered the Greek classics which included great works of geography by Egyptian Ptolemy's

Almagest and *Geography*, along with the geographical wisdom of the Chinese and the great accomplishments of the Roman Empire. The Arabs, who spoke only Arabic, employed Christians and Jews to translate these and many other manuscripts into Arabic.

The primary geographical scholarship of this era occurred in Persia, today's Iran, in the great learning center the House of Wisdom at Baghdad, today's Iraq. Early caliphs did not follow orthodoxy and so they encouraged scholarship. Under their rule, native non-Arabs served as *mawali* or *dhimmi*, and most geographers in this period were Syrian (Byzantine) or Persian, i.e. of either Zoroastrian or Christian background.

Persians who wrote on geography or created maps during the Middle Ages included:

- Jābir ibn Hayyān (Geber or Jabir) (721– c. 815) Wrote extensively on many subjects, expanded on the wisdom of the Greek classics and engaged in experimentation in natural science. It is unclear whether he was Persian or Syrian.
- Al-Khwārizmī (780–850) wrote *The Image of the Earth* (*Kitab surat al-ard*), in which he used the Geography (Ptolemy) of Ptolemy but improved upon his values for the Mediterranean Sea, Asia, and Africa.
- Ibn Khurdadhbih (820–912) authored a book of administrative geography *Book of the Routes and Provinces* (*Kitab al-masalik wa'l-mamalik*), which is the earliest surviving Arabic work of its kind. He made the first quadratic scheme map of four sectors.

- Sohrab or Sorkhab (died 930) wrote *Marvels of the Seven Climes to the End of Habitation* describing and illustrating a rectangular grid of latitude and longitude to produce a world map.
- Al-Balkhi (850–934) founded the "Balkhīschool" of terrestrial mapping in Baghdad.
- Al-Istakhri (died 957) compiled the *Book of the Routes of States,* (*Kitab Masalik al-Mamalik*) from personal observations and literary sources
- Al-Biruni (973–1052) described polar equi-azimuthal equidistant projection of the celestial sphere.
- Abu Nasr Mansur (960–1036) known for his work with the spherical sine law. His *Book of Azimuths* is no longer extant.
- Avicenna (980–1037) wrote on earth sciences in his *Book of Healing*.
- Ibn al-Faqih (10th century) wrote *Concise Book of Lands* (*Mukhtasar Kitab al-Buldan*).
- Ibn Rustah (10th century) wrote a geographical compendium known as *Book of Precious Records*.

Further details about some of these are given below:

In the early 10th century, Abū Zayd al-Balkhī, a Persian originally from Balkh, founded the "Balkhīschool" of terrestrial mapping in Baghdad. The geographers of this school also wrote extensively of the peoples, products, and customs of areas in the Muslim world, with little interest in the non-Muslim realms. Suhrāb, a late 10th-century Persian geographer, accompanied a book of geographical coordinates with instructions for making a rectangular world map, with equirectangular projection or cylindrical equidistant projection. In the early 11th century, Avicenna hypothesized on the geological causes of mountains in *The Book of Healing* (1027).

In mathematical geography, Persian Abū Rayhān al-Bīrūnī, around 1025, was the first to describe a polar equi-azimuthal equidistant projection of the celestial sphere. He was also regarded as the most skilled when it came to mapping cities and measuring the distances between them, which he did for many cities in the Middle East and western Indian subcontinent. He combined astronomical readings and mathematical equations to record degrees of latitude and longitude and to measure the heights of mountains and depths of valleys, recorded in *The Chronology of the Ancient Nations*. He discussed human geography and the planetary habitability of the Earth, suggesting that roughly a quarter of the Earth's surface is habitable by humans. He solved a complex geodesic equation in order to accurately compute the Earth's circumference. His estimate of 6,339.9 km for the Earth radius was only 16.8 km less than the modern value of 6,356.7 km.

By the early 12th century the Normans had overthrown the Arabs in Sicily. Palermo had become a crossroads for travelers and traders from many nations and the Norman King Roger II, having great interest in geography, commissioned the creation of a book and map that would compile all this wealth of geographical information. Researchers were sent out and the collection of data took 15 years. Al-Idrisi, one of few Arabs who had ever been to France and England as well as Spain, Central Asia and Constantinople, was employed to create the book from this mass of data. Utilizing the information inherited from the classical geographers, he created one of the most accurate maps of the world to date, the Tabula Rogeriana (1154). The map, written in Arabic, shows the Eurasian continent in its entirety and the northern part of Africa.

An adherent of environmental determinism was the medieval Afro-Arab writer al-Jahiz (776–869), who explained how the environment can determine the physical characteristics of the inhabitants of a certain community. He used his early theory of evolution to explain the origins of different human skin colors, particularly black skin, which he believed to be the result of the environment. He cited a stony region of black basalt in the northern Najd as evidence for his theory.

Medieval Europe

During the Early Middle Ages, geographical knowledge in Europe regressed (though it is a popular misconception that they thought the world was flat), and the simple T and O map became the standard depiction of the world.

The trips of Venetian explorer Marco Polo throughout Mongol Empire in the 13th century, the Christian Crusades of the 12th and 13th centuries, and the Portuguese and Spanish voyages of exploration during the 15th and 16th centuries opened up new horizons and stimulated geographic writings. The Mongols also had wide-ranging knowledge of the geography of Europe and Asia, based in their governance and ruling of much of this area and used this information for the undertaking of large military expeditions. The evidence for this is found in historical resources such as The Secret History of Mongols and other Persian chronicles written in 13th and 14th centuries. For example, during the rule of the Great Yuan Dynasty a world map was created and is currently kept in South Korea. See also: Maps of the Yuan Dynasty

During the 15th century, Henry the Navigator of Portugal supported explorations of the African coast and became a leader in the promotion of geographic studies. Among the most notable accounts of voyages and discoveries published during the 16th century were those by Giambattista Ramusio in Venice, by Richard Hakluyt in England, and by Theodore de Bry in what is now Belgium.

Early modern period

Following the journeys of Marco Polo, interest in geography spread throughout Europe. From around c. 1400, the writings of Ptolemy and his successors provided a systematic framework to tie together and portray geographical information. This framework was used by academics for centuries to come, the positives being the lead-up to the geographical enlightenment, however, women and indigenous writings were largely excluded from the discourse. The European global conquests started in the early 15th century with the first Portuguese expeditions to Africa and India, as well as the conquest of America by Spain in 1492 and continued with a series of European naval expeditions across the Atlantic and later the Pacific and Russian expeditions to Siberia until the 18th century. European overseas expansion led to the rise of colonial empires, with the contact between the "Old" and "New World"s producing the Columbian Exchange: a wide transfer of plants, animals, foods, human populations (including slaves), communicable diseases and culture between the continents.

These colonialist endeavours in 16th and 17th centuries revived a desire for both "accurate" geographic detail, and more solid theoretical foundations. The *Geographia Generalis* by Bernhardus Varenius and Gerardus Mercator's world map are prime examples of the new breed of scientific geography.

The Waldseemüller map *Universalis Cosmographia*, created by German cartographer Martin Waldseemüller in April 1507, is the first map of the Americas in which the name "America" is mentioned. Before this, the Native Americans referred to their land depending on their location, with one of the more commonly used terms being "Abya Yala", meaning "land of vital blood". These indigenous geographical discourses were largely ignored or appropriated by the European colonialists to make way for European thought.

The Eurocentric map was patterned after a modification of Ptolemy's second projection but expanded to include the Americas. The Waldseemuller Map has been called "America's birth certificate" Waldseemüller also created printed maps called globe gores, that could be cut out and glued to spheres resulting in a globe.

This has been debated widely as being dismissive of the extensive Native American history that predated the 16th-century invasion, in the sense that the implication of a "birth certificate" implies a blank history prior.

16th~18th centuries in the West

Geography as a science experiences excitement and exerts influence during the Scientific Revolution and Religion

Reformation. In the Victorian period, the oversea exploration gave it institutional identity and geography was "the science of imperialism par excellence." Imperialism is a crucial concept for the Europeans, as the institution become involved in geographical exploration and colonial project. Authority was questioned, and utility gained its importance. In the era of Enlightenment, geography generated knowledge and made it intellectually and practically possible as a university discipline. The natural theology required geography to investigate the world as a grand machine from the Divine. Scientific voyages and travels constructed geopolitical power from geographical knowledge, partly sponsored by Royal Society. John Pinkerton appraised the eighteenth century had "the gigantic progress of every science, and in particular of geographical information" and "alteration has taken place in states and boundaries."

The discourse of geographical history gave way to many new thoughts and theories, but the hegemony of the European male academia led to the exclusion of non-western theories, observations and knowledges. One such example is the interaction between humans and nature, with Marxist thought critiquing nature as a commodity within Capitalism, European thought seeing nature as either a romanticised or objective concept differing to human society, and Native American discourse, which saw nature and humans as within one category. The implied hierarchy of knowledge that perpetuated throughout these institutions has only been recently challenged, with the Royal Geographical Society enabling women to join as members in the 20th century.

After English Civil War, Samuel Hartlib and his Baconian community promoted scientific application, which showed the popularity of utility. For William Petty, the administrators should be "skilled in the best rules of judicial astrology" to "calculate the events of diseases and prognosticate the weather." Institutionally, Gresham College propagated scientific advancement to a larger audience like tradesmen, and later this institute grew into Royal Society. William Cuningham illustrated the utilitarian function of cosmography by the military implement of maps. John Dee used mathematics to study location—his primary interest in geography and encouraged exploiting resource with findings collected during voyages. Religion Reformation stimulated geographical exploration and investigation. Philipp Melanchthon shifted geographical knowledge production from "pages of scripture" to "experience in the world." Bartholomäus Keckermannseparated geography from theology because the "general workings of providence" required empirical investigation. His follower, Bernhardus Varenius made geography a science in the 17th century and published *Geographia Generalis*, which was used in Newton's teaching of geography at Cambridge.

Science develops along with empiricism. Empiricism gains its central place while reflection on it also grew. Practitioners of magic and astrology first embraced and expanded geographical knowledge. Reformation Theology focused more on the providence than the creation as previously. Realistic experience, instead of translated from scripture, emerged as a scientific procedure. Geographical knowledge and method play roles in economic education and administrative application, as part of the Puritan social program. Foreign travels provided content for geographic research and formed theories, such as environmentalism. Visual representation, map-making or cartography, showed its practical, theoretical, and artistic value.

The concepts of "Space" and "Place" attract attention in geography. Why things are there and not elsewhere is an important topic in Geography, together with debates on space and place. Such insights could date back in 16th and 17th centuries, identified by M. Curry as "Natural Space", "Absolute Space", "Relational Space" (*On Space and Spatial Practice*). After Descartes's *Principles of Philosophy*, Locke and Leibniz considered space as relative, which has long-term influence on the modern view of space. For Descartes, Grassendi and Newton, place is a portion of "absolution space", which are neural and given. However, according to John Locke, "Our Idea of Place is nothing else, but such a relative Position of any thing" (in *An Essay Concerning Human Understanding*). "Distance" is the pivot modification of space, because "Space considered barely in length between any two Beings, without considering any thing else between them". Also, the place is "made by Men, for their common use, that by it they might be able to design the particular Position of Things". In the *Fifth Paper in Reply to Clarke,* Leibniz stated: "Men fancy places, traces, and space, though these things consist only in the truth of relations and not at all in any absolute reality". Space, as an "order of coexistence", "can only be an ideal thing, containing a certain order, wherein the mind conceives the application of relation". Leibniz moved further for the term "distance" as he discussed it together with "interval" and "situation", not just a measurable character. Leibniz bridged place and space to quality and quantity, by saying "Quantity or magnitude is that in things which can be known only through their simultaneous compresence—or by their simultaneous perception... Quality, on the other hand, is what can be known in things when they are observed singly, without requiring any compresence." In *Modern Space as Relative*, place and what is in place are integrated. "The Supremacy of Space" is observed by E. Casey when the place is resolved as "position and even point" by Leibniz's rationalism and Locke's empiricism.

During Enlightenment, advancements in science mean widening human knowledge and enable further exploiting nature, along with industrialization and empire expansion in Europe. David Hume, "the real father of positivist philosophy" according to Leszek Kolakowski, implied the "doctrine of facts", emphasizing the importance of scientific observations. The "fact" is related with sensationalism that object cannot be isolated from its "sense-perceptions", an opinion of Berkeley. Galileo, Descartes, later Hobbes and Newton advocated scientific materialism, viewing the universe—the entire world and even human mind—as a machine. The mechanist world view is also found in the work of Adam Smith based on historical and statistics methods. In chemistry, Antoine Lavoisier proposed the "exact science model" and stressed quantitative methods from experiment and mathematics. Karl Linnaeus classified plants and organisms based on an assumption of fixed species. Later, the idea of evolution emerged not only for species but also for society and human intellect. In *General Natural History and Theory of the Heavens*, Kant laid out his hypothesis of cosmic evolution, and made him "the great founder of the modern scientific conception of Evolution" according to Hastie.

Francis Bacon and his followers believed progress of science and technology drive betterment of man. This belief was attached by Jean-Jacques Rousseau who defended human emotions and morals. His discussion on geography education piloted local regional studies. Leibniz and Kant formed the major challenge to the mechanical materialism. Leibniz conceptualized the world as a changing whole, rather than "sum of its parts" as a machine. Nevertheless, he acknowledged experience requires rational interpretation—the power of human reason.

Kant tried to reconcile the division of sense and reason by stressing moral rationalism grounded on aesthetic experience of nature as "order, harmony, and unity". For knowledge, Kant distinguished phenomena (*sensible* world) and noumena (*intelligible* world), and he asserted "all phenomena are perceived in the relations of space and time." Drawing a line between "rational science" and "empirical science", Kant regarded Physical geography—associating with space—as natural science. During his tenure in Königsberg, Kant offered lectures on physical geography since 1756 and published the lecture notes *Physische Geographie* in 1801. However, Kant's involvement in travel and geographical research is fairly limited. Kant's work on empirical and rational science influence Humboldt and at smaller extent Ritter. Manfred Büttner asserted that is "Kantian emancipation of geography from theology."

Humboldt is admired as a great geographer, according to D. Livingstone that "modern geography was first and last a synthesizing science and as such, if Goetzmann is to be believed, 'it became the key scientific activity of the age'."

Humboldt met the geographer George Forster at the University of Göttingen, whose geographical description and scientific writing influenced Humboldt. His *Geognosia* including the geography of rocks, animals, and plants is "an important model for modern geography". As the Prussian Ministry of Mines, Humboldt founded the Free Royal Mining School at Steben for miners, later regarded the prototype of such institutes. German Naturphilosophie, especially the work of Goethe and Herder, stimulated Humboldt's idea and research of a universal science. In his letter, he made observations while his "attention will never lose sight of the harmony of concurrent forces, the influence of the inanimate world on the animal and vegetable kingdom." His American travel stressed the geography of plants as his focus of science. Meanwhile, Humboldt used empirical method to study the indigenous people in the New World, regarded as a most important work in human geography. In *Relation historique du Voyage*, Humboldt called these research a new science *Physique du monde, Theorie de la Terre*, or *Geographie physique*. During 1825 to 1859, Humboldt devoted in Kosmos, which is about the knowledge of nature. There are growing works about the New World since then. In the Jeffersonian era, "American geography was born of the geography of America", meaning the knowledge discovery helped form the discipline. Practical knowledge and national pride are main components of the Teleological tradition.

Institutions such as the Royal Geographical Society indicate geography as an independent discipline. Mary Somerville's Physical Geography was the "conceptual culmination of ... Baconian ideal of universal integration". According to Francis Bacon, "No natural phenomenon can be adequately studied by itself alone – but, to be understood, it must be considered as it stands connected with all nature."

19th century

By the 18th century, geography had become recognized as a discrete discipline and became part of a typical university curriculum in Europe (especially Paris and Berlin), although not in the United Kingdom where geography was generally taught as a sub-discipline of other subjects.

A holistic view of geography and nature can be seen in the work by the 19th-century polymath Alexander von Humboldt. One of the great works of this time was Humboldt's *Kosmos: a sketch of a physical description of the Universe*, the first volume of which was published in German in 1845. Such was the power of this work that Dr Mary Somerville, of Cambridge University intended to scrap publication of her own *Physical Geography* on reading *Kosmos*. Von Humboldt himself persuaded her to publish (after the publisher sent him a copy).

In 1877, Thomas Henry Huxley published his Physiography with the philosophy of universality presented as an integrated approach in the study of the natural environment. The philosophy of universality in geography was not a new one but can be seen as evolving from the works of Alexander von Humboldt and Immanuel Kant. The publication of Huxley physiography presented a new form of geography that analysed and classified cause and effect at the micro-level and then applied these to the macro-scale (due to the view that the micro was part of the macro and thus an understanding of all the micro-scales was need to understand the macro level). This approach emphasized the empirical collection of data over the theoretical. The same approach was also used by Halford John Mackinder in 1887. However, the integration of the Geosphere, Atmosphere and Biosphere under physiography was soon over taken by Davisian geomorphology.

Over the past two centuries the quantity of knowledge and the number of tools has exploded. There are strong links between geography and the sciences of geology and botany, as well as economics, sociology and demographics.

The Royal Geographical Society was founded in England in 1830, although the United Kingdom did not get its first full Chair of geography until 1917. The first real geographical intellect to emerge in United Kingdom geography was Halford John Mackinder, appointed reader at Oxford University in 1887.

The National Geographic Society was founded in the United States in 1888 and began publication of the *National Geographic* magazine which became and continues to be a great popularizer of geographic information. The society has long supported geographic research and education.

20th century

In the West during the second half of the 19th and the 20th century, the discipline of geography went through four major phases: environmental determinism, regional geography, the quantitative revolution, and critical geography.

Environmental determinism

Environmental determinism is the theory that a people's physical, mental and moral habits are directly due to the influence of their natural environment. Prominent environmental determinists included Carl Ritter, Ellen Churchill Semple, and Ellsworth Huntington. Popular hypotheses included "heat makes inhabitants of the tropics lazy" and "frequent changes in barometric pressure make inhabitants of temperate latitudes more intellectually agile." Environmental determinist geographers attempted to make the study of such influences scientific. Around the 1930s, this school of thought was widely repudiated as lacking any basis and being prone to (often bigoted) generalizations. Environmental determinism remains an embarrassment to many contemporary geographers, and leads to skepticism among many of them of claims of environmental influence on culture (such as the theories of Jared Diamond).

Regional geography

Regional geography was coined by a group of geographers known as possibilists and represented a reaffirmation that the proper topic of geography was study of places (regions). Regional geographers focused on the collection of descriptive information about places, as well as the proper methods for dividing the earth up into regions. Well-known names from these period are Alfred Hettner in Germany and Paul Vidal de la Blache in France. The philosophical basis of this field in United States was laid out by Richard Hartshorne, who defined geography as a study of areal differentiation, which later led to criticism of this approach as overly descriptive and unscientific.

However, the concept of a Regional geography model focused on Area Studies has remained incredibly popular amongst students of geography, while less so amongst scholars who are proponents of Critical Geography and reject a Regional geography paradigm. It can be argued that Regional Geography, which during its heyday in the 1970s through early 1990s made substantive contributions to students' and readers' understanding of foreign cultures and the real world effects of the delineation of borders, is due for a revival in academia as well as in popular nonfiction.

The quantitative revolution

The **quantitative revolution** in geography began in the 1950s. Geographers formulated geographical theories and subjected the theories to empirical tests, usually using statistical methods (especially hypothesis testing). This quantitative revolution laid the groundwork for the development of geographic information systems. Well-known geographers from this period are Fred K. Schaefer, Waldo Tobler, William Garrison, Peter Haggett, Richard J. Chorley, William Bunge, Edward Augustus Ackerman and Torsten Hägerstrand.

Critical geography

Though positivist approaches remain important in geography, **critical geography** arose as a critique of positivism. The first strain of critical geography to emerge was humanistic geography. Drawing on the philosophies of existentialism and phenomenology, humanistic geographers (such as Yi-Fu Tuan) focused on people's sense of, and relationship with, places. More influential was Marxist geography, which applied the social theories of Karl Marx and his followers to geographic phenomena. David Harvey and Richard Peet are well-known Marxist geographers. Feminist geography is, as the name suggests, the use of ideas from feminism in geographic contexts. The most recent strain of critical geography is postmodernist geography, which employs the ideas of postmodernist and poststructuralist theorists to explore the social construction of spatial relations.

Chapter 23

History of Geology

The **history of geology** is concerned with the development of the natural science of geology. Geology is the scientific study of the origin, history, and structure of the earth.

Antiquity

Some of the first geological thoughts were about the origin of the earth. Ancient Greece developed some primary geological concepts concerning the origin of the earth. Additionally, in the 4th century BC Aristotle made critical observations of the slow rate of geological change. He observed the composition of the land and formulated a theory where the earth changes at a slow rate and that these changes cannot be observed during one person's lifetime. Aristotle developed one of the first evidence-based concepts connected to the geological realm regarding the rate at which the earth physically changes.

However, it was his successor at the Lyceum, the philosopher Theophrastus, who made the greatest progress in antiquity in his work *On Stones*. He described many minerals and ores both from local mines such as those at Laurium near Athens, and further afield. He also quite naturally discussed types of marble and building materials like limestones, and attempted a primitive classification of the properties of minerals by their properties such as hardness.

Much later in the Roman period, Pliny the Elder produced a very extensive discussion of many more minerals and metals then widely used for practical ends. He was among the first to correctly identify the origin of amber as a fossilized resin from trees by the observation of insects trapped within some pieces. He also laid the basis of crystallography by recognising the octahedral habit of diamond.

Middle Ages

Abu al-Rayhan al-Biruni (AD 973–1048) was one of the earliest Muslim geologists, whose works included the earliest writings on the geology of India, hypothesizing that the Indian subcontinent was once a sea.

Ibn Sina (Avicenna, AD 981–1037), a Persian polymath, made significant contributions to geology and the natural sciences (which he called *Attabieyat*) along with other natural philosophers such as Ikhwan AI-Safa and many others. Ibn Sina wrote an encyclopedic work entitled "*Kitab al-Shifa*" (the Book of Cure, Healing or Remedy from ignorance), in which Part 2, Section 5, contains his commentary on Aristotle's Mineralogy and Meteorology, in six chapters: Formation of mountains, The advantages of mountains in the formation of clouds; Sources of water; Origin of earthquakes; Formation of minerals; The diversity of the earth's terrain.

In medieval China, one of the most intriguing naturalists was Shen Kuo (1031–1095), a polymath personality who dabbled in many fields of study in his age. In terms of geology, Shen Kuo is one of the first naturalists to have formulated a theory of geomorphology. This was based on his observations of sedimentary uplift, soil erosion, deposition of silt, and marine fossils found in the Taihang Mountains, located hundreds of miles from the Pacific Ocean. He also formulated a theory of gradual climate change, after his observation of ancient petrified bamboos found in a preserved state underground near Yanzhou (modern Yan'an), in the dry northern climate of Shaanxi province. He formulated a hypothesis for the process of land formation: based on his observation of fossil shells in a geological stratum in a mountain hundreds of miles from the ocean, he inferred that the land was formed by erosion of the mountains and by deposition of silt.

17th century

It was not until the 17th century that geology made great strides in its development. At this time, geology became its own entity in the world of natural science. It was discovered by the Christian world that different translations of the Bible contained different versions of the biblical text. The one entity that remained consistent through all of the interpretations was that the Deluge had formed the world's geology and geography. To prove the Bible's authenticity, individuals felt the need to demonstrate with scientific evidence that the Great Flood had in fact occurred. With this enhanced desire for data came an increase in observations of the earth's composition, which in turn led to the discovery of fossils. Although theories that resulted from the heightened interest in the earth's composition were often manipulated to support the concept of the Deluge, a genuine outcome was a greater interest in the makeup of the earth. Due to the strength of Christian beliefs during the 17th century, the theory of the origin of the Earth that was most widely accepted was *A New Theory of the Earth* published in 1696, by William Whiston. Whiston used Christian reasoning to "prove" that the Great Flood had occurred and that the flood had formed the rock strata of the earth.

During the 17th century, both religious and scientific speculation about the earth's origin further propelled interest in the earth and brought about more systematic identification techniques of the earth's strata. The earth's strata can be defined as horizontal layers of rock having approximately the same composition throughout. An important pioneer in the science was Nicolas Steno. Steno was trained in the classical texts on science; however, by 1659 he seriously questioned accepted knowledge of the natural world. Importantly, he questioned the idea that fossils grew in the ground, as well as common explanations of rock formation. His investigations and his subsequent conclusions on these topics have led scholars to consider him one of the founders of modern stratigraphy and geology. (Steno, who became a Catholic as an adult, was eventually made a bishop, and was beatified in 1988 by Pope John Paul II. Therefore, he is also called Blessed Nicolas Steno.)

18th century

From this increased interest in the nature of the earth and its origin, came a heightened attention to minerals and other components of the earth's crust. Moreover, the increasing economic importance of mining in Europe during the mid to late 18th century made the possession of accurate knowledge about ores and their natural distribution vital. Scholars began to study the makeup of the earth in a systematic manner, with detailed comparisons and descriptions not only of the land itself, but of the semi-precious metals it contained, which had great commercial value. For example, in 1774 Abraham Gottlob Werner published the book *Von den äusserlichen Kennzeichen der Fossilien (On the External Characters of Minerals),* which brought him widespread recognition because he presented a detailed system for identifying specific minerals based on external characteristics. The more efficiently productive land for mining could be identified and the semi-precious metals could be found, the more money could be made. This drive for economic gain propelled geology into the limelight and made it a popular subject to pursue. With an increased number of people studying it, came more detailed observations and more information about the earth.

Also during the eighteenth century, aspects of the history of the earth—namely the divergences between the accepted religious concept and factual evidence—once again became a popular topic for discussion in society. In 1749, the French naturalist Georges-Louis Leclerc, Comte de Buffon published his *Histoire Naturelle,* in which he attacked the popular Biblical accounts given by Whiston and other ecclesiastical theorists of the history of the earth. From experimentation with cooling globes, he found that the age of the earth was not only 4,000 or 5,500 years as inferred from the Bible, but rather 75,000 years. Another individual who described the history of the earth with reference to neither God nor the Bible was the philosopher Immanuel Kant, who published his *Universal Natural History and Theory of the Heavens (Allgemeine*

Naturgeschichte und Theorie des Himmels) in 1755. From the works of these respected men, as well as others, it became acceptable by the mid eighteenth century to question the age of the earth. This questioning represented a turning point in the study of the earth. It was now possible to study the history of the earth from a scientific perspective without religious preconceptions.

With the application of scientific methods to the investigation of the earth's history, the study of geology could become a distinct field of science. To begin with, the terminology and definition of what constituted geological study had to be worked out. The term "geology" was first used technically in publications by two Genevan naturalists, Jean-André Deluc and Horace-Bénédict de Saussure, though "geology" was not well received as a term until it was taken up in the very influential compendium, the *Encyclopédie*, published beginning in 1751 by Denis Diderot. Once the term was established to denote the study of the earth and its history, geology slowly became more generally recognized as a distinct science that could be taught as a field of study at educational institutions. In 1741 the best-known institution in the field of natural history, the National Museum of Natural History in France, created the first teaching position designated specifically for geology. This was an important step in further promoting knowledge of geology as a science and in recognizing the value of widely disseminating such knowledge.

By the 1770s, chemistry was starting to play a pivotal role in the theoretical foundation of geology and two opposite theories with committed followers emerged. These contrasting theories offered differing explanations of how the rock layers of the earth's surface had formed. One suggested that a liquid inundation, perhaps like the biblical deluge, had created all geological strata. The theory extended chemical theories that had been developing since the seventeenth century and was promoted by Scotland's John Walker, Sweden's Johan Gottschalk Wallerius and Germany's Abraham Werner. Of these names, Werner's views become internationally influential around 1800. He argued that the earth's layers, including basalt and granite, had formed as a precipitate from an ocean that covered the entire earth. Werner's system was influential and those who accepted his theory were known as Diluvianists or Neptunists. The Neptunist thesis was the most popular during the late eighteenth century, especially for those who were chemically trained. However, another thesis slowly gained currency from the 1780s forward. Instead of water, some mid eighteenth-century naturalists such as Buffon had suggested that strata had been formed through heat (or fire). The thesis was modified and expanded by the Scottish naturalist James Hutton during the 1780s. He argued against the theory of Neptunism, proposing instead the theory of based on heat. Those who followed this thesis during the early nineteenth century referred to this view as Plutonism: the formation of the earth through the gradual solidification of a molten mass at a slow rate by the same processes that had occurred throughout history and continued in the present day. This led him to the conclusion that the earth was immeasurably old and could not possibly be explained within the limits of the chronology inferred from the Bible. Plutonists believed that volcanic processes were the chief agent in rock formation, not water from a Great Flood.

19th century

- In the early 19th century, the mining industry and Industrial Revolution stimulated the rapid development of the stratigraphic column – "the sequence of rock formations arranged according to their order of formation in time." In England, the mining surveyor William Smith, starting in the 1790s, found empirically that fossils were a highly effective means of distinguishing between otherwise similar formations of the landscape as he travelled the country working on the canal system and produced the first geological map of Britain. At about the same time, the French comparative anatomist Georges Cuvier assisted by his colleague Alexandre Brogniart at the École des Mines de Paris realized that the relative ages of fossils could be determined from a geological standpoint; in terms of what layer of rock the fossils are located and the distance these layers of rock are from the surface of the earth. Through the synthesis of their findings, Brogniart and Cuvier realized that different strata could be identified by fossil contents and thus each stratum could be assigned to a unique position in a sequence. After the publication of Cuvier and Brongniart's book, "Description Geologiques des Environs de Paris" in 1811, which outlined the concept, stratigraphy became very popular amongst geologists; many hoped to apply this concept to all the rocks of the earth. During this century various geologists further refined and completed the stratigraphic column. For instance, in 1833 while Adam Sedgwick was mapping rocks that he had established were from the Cambrian Period, Charles Lyell was elsewhere suggesting a subdivision of the Tertiary Period; whilst Roderick Murchison, mapping into Wales from a different direction, was assigning the upper parts of Sedgwick's *Cambrian* to the lower parts of his own Silurian Period. The stratigraphic column was significant because it supplied a method to assign a relative age of these rocks by slotting them into different positions in their stratigraphical sequence. This created a global approach to dating the age of the earth and allowed for further correlations to be drawn from similarities found in the makeup of the earth's crust in various countries.

In early nineteenth-century Britain, catastrophism was adapted with the aim of reconciling geological science with religious traditions of the biblical Great Flood. In the early 1820s English geologists including William Buckland and Adam Sedgwick interpreted "diluvial" deposits as the outcome of Noah's flood, but by the end of the decade they revised their opinions in favour of local inundations. Charles Lyell challenged catastrophism with the publication in 1830 of the first volume of his book *Principles of Geology* which presented a variety of geological evidence from England, France, Italy and Spain to prove Hutton's ideas of gradualism correct. He argued that most geological change had been very gradual in human history. Lyell provided evidence for Uniformitarianism; a geological doctrine that processes occur at the same rates in the present as they did in the past and account for all of the earth's geological features. Lyell's works were popular and widely read, the concept of Uniformitarianism had taken a strong hold in geological society.

In 1831 Captain Robert FitzRoy, given charge of the coastal survey expedition of HMS *Beagle*, sought a suitable naturalist to examine the land and give geological advice. This fell to Charles Darwin, who had just completed his BA degree and had accompanied Sedgwick on a two-week Welsh mapping expedition after taking his Spring course on geology. Fitzroy gave Darwin Lyell's *Principles of Geology*, and Darwin became and advocate of Lyell ideas, inventively theorising on uniformitarian principles about the geological processes he saw, and even challenging some of Lyell's ideas. He speculated about the earth expanding to explain uplift, then on the basis of the idea that ocean areas sank as land was uplifted, theorised that coral atolls grew from fringing coral reefs round sinking volcanic islands. This idea was confirmed when the *Beagle* surveyed the Cocos (Keeling) Islands, and in 1842 he published his theory on *The Structure and Distribution of Coral Reefs*. Darwin's discovery of giant fossils helped to establish his reputation as a geologist, and his theorising about the causes of their extinction led to his theory of evolution by natural selection published in *On the Origin of Species* in 1859.

Economic motivations for the practical use of geological data motivated some governments to support geological research. During the 19th century several countries, including Canada, Australia, Great Britain and the United States, initiated geological surveying that would produce geological maps of vast areas of the countries. Geological mapping provides the location of useful rocks and minerals and such information could be used to benefit the country's mining and quarrying industries. With the government and industrial funding of geological research, more individuals undertook study of geology as technology and techniques improved, leading to the expansion of the field of the science.

In the 19th century, geological inquiry had estimated the age of the earth in terms of millions of years. In 1862, the physicist William Thomson, 1st Baron Kelvin, published calculations that fixed the age of earth at between 20 million and 400 million years. He assumed that earth had formed as a completely molten object, and determined the amount of time it would take for the near-surface to cool to its present temperature. Many geologists contended that Thomson's estimates were inadequate to account for observed thicknesses of sedimentary rock, evolution of life, and the formation of the crystalline basement rocks beneath the sedimentary cover. The discovery of radioactivity in the early Twentieth Century provided an additional source of heat within the earth, allowing for an increase in Thomson's calculated age, as well as a means of dating geological events.

20th century

By the early 20th Century radiogenic isotopes had been discovered and Radiometric Dating had been developed. In 1911 Arthur Holmes, among the pioneers in the use of radioactive decay as a mean to measure geological time, dated a sample from Ceylon at 1.6 billion years old using lead isotopes. In 1913 Holmes was on the staff of Imperial College, when he published his famous book *The Age of the Earth* in which he argued strongly in favour of the use of radioactive dating methods rather than methods based on geological sedimentation or cooling of the earth (many people still clung to Lord Kelvin's calculations of less than 100 million years). Holmes estimated the oldest Archean rocks to be 1,600 million years, but did not speculate about the earth's age. His promotion of the theory over the next decades earned him the nickname of Father of Modern Geochronology. In 1921, attendees at the yearly meeting of the British Association for the Advancement of Science came to a rough consensus that the Age of the earth was a few billion years old, and that radiometric dating was credible. Holmes published The Age of the Earth, an Introduction to Geological Ideas in 1927 in which he presented a range of 1.6 to 3.0 billion years. and in the 1940s to 4,500±100 million years, based on measurements of the relative abundance of uranium isotopes established by Alfred O. C. Nier. Theories that did not comply with the scientific evidence that established the age of the earth could no longer be accepted. The established age of the earth has been refined since then but has not significantly changed.

In 1912 Alfred Wegener proposed the theory of continental drift. This theory suggests that the shapes of continents and matching coastline geology between some continents indicates they were joined together in the past and formed a single landmass known as Pangaea; thereafter they separated and drifted like rafts over the ocean floor, currently reaching their present position. Additionally, the theory of continental drift offered a possible explanation as to the formation of mountains; plate tectonics built on the theory of continental drift.

Unfortunately, Wegener provided no convincing mechanism for this drift, and his ideas were not generally accepted during his lifetime. Arthur Holmes accepted Wegener's theory and provided a mechanism: mantle convection, to cause the continents to move. However, it was not until after the Second World War that new evidence started to accumulate that supported continental drift. There followed a period of 20 extremely exciting years where the theory of continental drift developed from being believed by a few to being the cornerstone of modern geology. Beginning in 1947 research provided new evidence about the ocean floor, and in 1960 Bruce C. Heezen published the concept of mid-ocean ridges. Soon after this, Robert S. Dietz and Harry H. Hess proposed that the oceanic crust forms as the seafloor spreads apart along mid-ocean ridges in seafloor spreading. This was seen as confirmation of mantle convection and so the major stumbling block to the theory was removed. Geophysical evidence suggested lateral motion of continents and that oceanic crust is younger than continental crust. This geophysical evidence also spurred the hypothesis of paleomagnetism, the record of the orientation of the earth's magnetic field recorded in magnetic minerals. British geophysicist S. K. Runcorn suggested the concept of paleomagnetism from his finding that the continents had moved relative to the earth's magnetic poles. Tuzo Wilson, who was a promoter of the sea floor spreading hypothesis and continental drift from the very beginning, added the concept of transform faults to the model, completing the classes of fault types necessary to make the mobility of the plates on the globe function. A symposium on continental drift was held at the Royal Society of London in 1965 must be regarded as the official start of the acceptance of plate tectonics by the scientific community. The abstracts from the symposium are issued as Blacket, Bullard, Runcorn;1965.In this symposium, Edward Bullard and co-workers showed with a computer calculation how the continents along both sides of the Atlantic would best fit to close the ocean, which became known as the famous "Bullard's Fit". By the late 1960s the weight of the evidence available saw Continental Drift as the generally accepted theory.

Modern geology

By applying sound stratigraphic principles to the distribution of craters on the Moon, it can be argued that almost overnight, Gene Shoemaker took the study of the Moon away from Lunar astronomers and gave it to Lunar geologists.

In recent years, geology has continued its tradition as the study of the character and origin of the earth, its surface features and internal structure. What changed in the later 20th century is the perspective of geological study. Geology was now studied using a more integrative approach, considering the earth in a broader context encompassing the atmosphere, biosphere and hydrosphere. Satellites located in space that take wide scope photographs of the earth provide such a perspective. In 1972, The Landsat Program, a series of satellite missions jointly managed by NASA and the U.S. Geological Survey, began supplying satellite images that can be geologically analyzed. These images can be used to map major geological units, recognize and correlate rock types for vast regions and track the movements of Plate Tectonics. A few applications of this data include the ability to produce geologically detailed maps, locate sources of natural energy and predict possible natural disasters caused by plate shifts.

Chapter 24

History of Meteorology

The ability to predict rains and floods based on annual cycles was evidently used by humans at least from the time of agricultural settlement if not earlier. Early approaches to predicting weather were based on astrology and were practiced by priests. Cuneiform inscriptions on Babylonian tablets included associations between thunder and rain. The Chaldeans differentiated the 22° and 46° halos.

Ancient Indian Upanishads contain mentions of clouds and seasons. The Samaveda mentions sacrifices to be performed when certain phenomena were noticed. Varāhamihira's classical work *Brihatsamhita*, written about 500 AD, provides evidence of weather observation.

In 350 BC, Aristotle wrote *Meteorology*. Aristotle is considered the founder of meteorology. One of the most impressive achievements described in the *Meteorology* is the description of what is now known as the hydrologic cycle.

The book De Mundo (composed before 250 BC or between 350 and 200 BC) noted:

- If the flashing body is set on fire and rushes violently to the Earth it is called a thunderbolt; if it is only half of fire, but violent also and massive, it is called a *meteor*; if it is entirely free from fire, it is called a smoking bolt. They are all called 'swooping bolts' because they swoop down upon the Earth.

> Lightning is sometimes smoky, and is then called 'smoldering lightning"; sometimes it darts quickly along, and is then said to be *vivid*. At other times, it travels in crooked lines, and is called *forked lightning*. When it swoops down upon some object it is called 'swooping lightning'.

The Greek scientist Theophrastus compiled a book on weather forecasting, called the *Book of Signs*. The work of Theophrastus remained a dominant influence in the study of weather and in weather forecasting for nearly 2,000 years. In 25 AD, Pomponius Mela, a geographer for the Roman Empire, formalized the climatic zone system. According to Toufic Fahd, around the 9th century, Al-Dinawari wrote the *Kitab al-Nabat* (*Book of Plants*), in which he deals with the application of meteorology to agriculture during the Arab Agricultural Revolution. He describes the meteorological character of the sky, the planets and constellations, the sun and moon, the lunar phases indicating seasons and rain, the *anwa* (heavenly bodies of rain), and atmospheric phenomena such as winds, thunder, lightning, snow, floods, valleys, rivers, lakes.

Early attempts at predicting weather were often related to prophecy and divining, and were sometimes based on astrological ideas. Admiral FitzRoy tried to separate scientific approaches from prophetic ones.

Research of visual atmospheric phenomena

Ptolemy wrote on the atmospheric refraction of light in the context of astronomical observations. In 1021, Alhazen showed that atmospheric refraction is also responsible for twilight; he estimated that twilight begins when the sun is 19 degrees below the horizon, and also used a geometric determination based on this to estimate the maximum possible height of the Earth's atmosphere as 52,000 *passim* (about 49 miles, or 79 km).

St. Albert the Great was the first to propose that each drop of falling rain had the form of a small sphere, and that this form meant that the rainbow was produced by light interacting with each raindrop. Roger Bacon was the first to calculate the angular size of the rainbow. He stated that a rainbow summit can not appear higher than 42 degrees above the horizon. In the late 13th century and early 14th century, Kamāl al-Dīn al-Fārisī and Theodoric of Freiberg were the first to give the correct explanations for the primary rainbow phenomenon. Theoderic went further and also explained the secondary rainbow. In 1716, Edmund Halley suggested that aurorae are caused by "magnetic effluvia" moving along the Earth's magnetic field lines.

Instruments and classification scales

In 1441, King Sejong's son, Prince Munjong of Korea, invented the first standardized rain gauge. These were sent throughout the Joseon dynasty of Korea as an official tool to assess land taxes based upon a farmer's potential harvest. In 1450, Leone Battista Alberti developed a swinging-plate anemometer, and was known as the first *anemometer*. In 1607, Galileo Galilei constructed a thermoscope. In 1611, Johannes Kepler wrote the first scientific treatise on snow crystals: "Strena Seu de Nive Sexangula (A New Year's Gift of Hexagonal Snow)." In 1643, Evangelista Torricelli invented the mercury barometer.

In 1662, Sir Christopher Wren invented the mechanical, self-emptying, tipping bucket rain gauge. In 1714, Gabriel Fahrenheit created a reliable scale for measuring temperature with a mercury-type thermometer. In 1742, Anders Celsius, a Swedish astronomer, proposed the "centigrade" temperature scale, the predecessor of the current Celsius scale. In 1783, the first hair hygrometer was demonstrated by Horace-Bénédict de Saussure. In 1802–1803, Luke Howard wrote *On the Modification of Clouds*, in which he assigns cloud types Latin names. In 1806, Francis Beaufort introduced his system for classifying wind speeds. Near the end of the 19th century the first cloud atlases were published, including the *International Cloud Atlas*, which has remained in print ever since. The April 1960 launch of the first successful weather satellite, TIROS-1, marked the beginning of the age where weather information became available globally.

Atmospheric composition research

In 1648, Blaise Pascal rediscovered that atmospheric pressure decreases with height, and deduced that there is a vacuum above the atmosphere. In 1738, Daniel Bernoulli published *Hydrodynamics*, initiating the Kinetic theory of gases and established the basic laws for the theory of gases. In 1761, Joseph Black discovered that ice absorbs heat without changing its temperature when melting. In 1772, Black's student Daniel Rutherford discovered nitrogen, which he called *phlogisticated air*, and together they developed the phlogiston theory. In 1777, Antoine Lavoisier discovered oxygen and developed an explanation for combustion. In 1783, in Lavoisier's essay "Reflexions sur le phlogistique," he deprecates the phlogiston theory and proposes a caloric theory. In 1804, Sir John Leslie observed that a matte black surface radiates heat more effectively than a polished surface, suggesting the importance of black-body radiation. In 1808, John Dalton defended caloric theory in *A New System of Chemistry* and described how it combines with matter, especially gases; he proposed that the heat capacity of gases varies inversely with atomic weight. In 1824, Sadi Carnot analyzed the efficiency of steam engines using caloric theory; he developed the notion of a reversible process and, in postulating that no such thing exists in nature, laid the foundation for the second law of thermodynamics.

Research into cyclones and air flow

In 1494, Christopher Columbus experienced a tropical cyclone, which led to the first written European account of a hurricane. In 1686, Edmund Halley presented a systematic study of the trade winds and monsoons and identified solar heating as the cause of atmospheric motions. In 1735, an *ideal* explanation of global circulation through study of the trade winds was written by George Hadley. In 1743, when Benjamin Franklin was prevented from seeing a lunar eclipse by a hurricane, he decided that cyclones move in a contrary manner to the winds at their periphery. Understanding the kinematics of how exactly the rotation of the Earth affects airflow was partial at first. Gaspard-Gustave Coriolis published a paper in 1835 on the energy yield of machines with rotating parts, such as waterwheels. In 1856, William Ferrel proposed the existence of a circulation cell in the mid-latitudes, and the air within deflected by the Coriolis force resulting in the prevailing westerly winds. Late in the 19th century, the motion of air masses along isobars was understood to be the result of the large-scale interaction of the pressure gradient force and the deflecting force. By 1912, this deflecting force was named the Coriolis effect. Just after World War I, a group of meteorologists in Norway led by Vilhelm Bjerknes developed the Norwegian cyclone model that explains the generation, intensification and ultimate decay (the life cycle) of mid-latitude cyclones, and introduced the idea of fronts, that is, sharply defined boundaries between air masses. The group included Carl-Gustaf Rossby (who was the first to explain the large scale atmospheric flow in terms of fluid dynamics), Tor Bergeron (who first determined how rain forms) and Jacob Bjerknes.

Observation networks and weather forecasting

In the late 16th century and first half of the 17th century a range of meteorological instruments were invented – the thermometer, barometer, hydrometer, as well as wind and rain gauges. In the 1650s natural philosophers started using these instruments to systematically record weather observations. Scientific academies established weather diaries and organised observational networks. In 1654, Ferdinando II de Medici established the first *weather observing*network, that consisted of meteorological stations in Florence, Cutigliano, Vallombrosa, Bologna, Parma, Milan, Innsbruck, Osnabrück, Paris and Warsaw. The collected data were sent to Florence at regular time intervals. In the 1660s Robert Hooke of the Royal Society of London sponsored networks of weather observers. Hippocrates' treatise *Airs, Waters, and Places* had linked weather to disease. Thus early meteorologists attempted to correlate weather patterns with epidemic outbreaks, and the climate with public health.

During the Age of Enlightenment meteorology tried to rationalise traditional weather lore, including astrological meteorology. But there were also attempts to establish a theoretical understanding of weather phenomena. Edmond Halley and George Hadley tried to explain trade winds. They reasoned that the rising mass of heated equator air is replaced by an inflow of cooler air from high latitudes. A flow of warm air at high altitude from equator to poles in turn established an early picture of circulation. Frustration with the lack of discipline among weather observers, and the poor quality of the instruments, led the early modern nation states to organise large observation networks. Thus by the end of the 18th century, meteorologists had access to large quantities of reliable weather data. In 1832, an electromagnetic telegraph was created by Baron Schilling. The arrival of the electrical telegraph in 1837 afforded, for the first time, a practical method for quickly gathering surface weather observations from a wide area.

This data could be used to produce maps of the state of the atmosphere for a region near the Earth's surface and to study how these states evolved through time. To make frequent weather forecasts based on these data required a reliable network of observations, but it was not until 1849 that the Smithsonian Institution began to establish an observation network across the United States under the leadership of Joseph Henry. Similar observation networks were established in Europe at this time. The Reverend William Clement Ley was key in understanding of cirrus clouds and early understandings of Jet Streams. Charles Kenneth Mackinnon Douglas, known as 'CKM' Douglas read Ley's papers after his death and carried on the early study of weather systems. Nineteenth century researchers in meteorology were drawn from military or medical backgrounds, rather than trained as dedicated scientists. In 1854, the United Kingdom government appointed Robert FitzRoy to the new office of *Meteorological Statist to the Board of Trade* with the task of gathering weather observations at sea. FitzRoy's office became the United Kingdom Meteorological Office in 1854, the second oldest national meteorological service in the world (the Central Institution for Meteorology and Geodynamics (ZAMG) in Austria was founded in 1851 and is the oldest weather service in the world). The first daily weather forecasts made by FitzRoy's Office were published in *The Times* newspaper in 1860. The following year a system was introduced of hoisting storm warning cones at principal ports when a gale was expected.

Over the next 50 years, many countries established national meteorological services. The India Meteorological Department (1875) was established to follow tropical cyclone and monsoon. The Finnish Meteorological Central Office (1881) was formed from part of Magnetic Observatory of Helsinki University. Japan's Tokyo Meteorological Observatory, the forerunner of the Japan Meteorological Agency, began constructing surface weather maps in 1883. The United States Weather Bureau (1890) was established under the United States Department of Agriculture. The Australian Bureau of Meteorology (1906) was established by a Meteorology Act to unify existing state meteorological services.

Numerical weather prediction

In 1904, Norwegian scientist Vilhelm Bjerknes first argued in his paper *Weather Forecasting as a Problem in Mechanics and Physics* that it should be possible to forecast weather from calculations based upon natural laws.

It was not until later in the 20th century that advances in the understanding of atmospheric physics led to the foundation of modern numerical weather prediction. In 1922, Lewis Fry Richardson published "Weather Prediction By Numerical Process," after finding notes and derivations he worked on as an ambulance driver in World War I. He described how small terms in the prognostic fluid dynamics equations that govern atmospheric flow could be neglected, and a numerical calculation scheme that could be devised to allow predictions. Richardson envisioned a large auditorium of thousands of people performing the calculations. However, the sheer number of calculations required was too large to complete without electronic computers, and the size of the grid and time steps used in the calculations led to unrealistic results. Though numerical analysis later found that this was due to numerical instability.

Starting in the 1950s, numerical forecasts with computers became feasible. The first weather forecasts derived this way used barotropic (single-vertical-level) models, and could successfully predict the large-scale movement of midlatitude Rossby waves, that is, the pattern of atmospheric lows and highs. In 1959, the UK Meteorological Office received its first computer, a Ferranti Mercury.

In the 1960s, the chaotic nature of the atmosphere was first observed and mathematically described by Edward Lorenz, founding the field of chaos theory. These advances have led to the current use of ensemble forecasting in most major forecasting centers, to take into account uncertainty arising from the chaotic nature of the atmosphere. Mathematical models used to predict the long term weather of the Earth (climate models), have been developed that have a resolution today that are as coarse as the older weather prediction models. These climate models are used to investigate long-term climate shifts, such as what effects might be caused by human emission of greenhouse gases.

- The **timeline of meteorology** contains events of scientific and technological advancements in the area of atmospheric sciences. The most notable advancements in observational meteorology, weather forecasting, climatology, atmospheric chemistry, and atmospheric physics are listed chronologically. Some historical weather events are included that mark time periods where advancements were made, or even that sparked policy change.

Antiquity

- 3000 BC – Meteorology in India can be traced back to around 3000 BC, with writings such as the Upanishads, containing discussions about the processes of cloud formation and rain and the seasonal cycles caused by the movement of earth round the sun.

- 600 BC – Thales may qualify as the first Greek meteorologist. He reputedly issues the first seasonal crop forecast.
- 400 BC – There is some evidence that Democritus predicted changes in the weather, and that he used this ability to convince people that he could predict other future events.
- 400 BC – Hippocrates writes a treatise called *Airs, Waters and Places*, the earliest known work to include a discussion of weather. More generally, he wrote about common diseases that occur in particular locations, seasons, winds and air.
- 350 BC – The Greek philosopher Aristotle writes *Meteorology*, a work which represents the sum of knowledge of the time about earth sciences, including weather and climate. It is the first known work that attempts to treat a broad range of meteorological topics. For the first time, precipitation and the clouds from which precipitation falls are called meteors, which originate from the Greek word *meteoros*, meaning 'high in the sky'. From that word comes the modern term meteorology, the study of clouds and weather.
- Although the term *meteorology* is used today to describe a subdiscipline of the atmospheric sciences, Aristotle's work is more general. Meteorologica is based on intuition and simple observation, but not on what is now considered the scientific method. In his own words:
- *...all the affections we may call common to air and water, and the kinds and parts of the earth and the affections of its parts.*

- The magazine *De Mundo* (attributed to Pseudo-Aristotle) notes:
- *Cloud is a vaporous mass, concentrated and producing water. Rain is produced from the compression of a closely condensed cloud, varying according to the pressure exerted on the cloud; when the pressure is slight it scatters gentle drops; when it is great it produces a more violent fall, and we call this a shower, being heavier than ordinary rain, and forming continuous masses of water falling over earth. Snow is produced by the breaking up of condensed clouds, the cleavage taking place before the change into water; it is the process of cleavage which causes its resemblance to foam and its intense whiteness, while the cause of its coldness is the congelation of the moisture in it before it is dispersed or rarefied. When snow is violent and falls heavily we call it a blizzard. Hail is produced when snow becomes densified and acquires impetus for a swifter fall from its close mass; the weight becomes greater and the fall more violent in proportion to the size of the broken fragments of cloud. Such then are the phenomena which occur as the result of moist exhalation.*
- One of the most impressive achievements in *Meteorology* is his description of what is now known as the hydrologic cycle:
- *Now the sun, moving as it does, sets up processes of change and becoming and decay, and by its agency the finest and sweetest water is every day carried up and is dissolved into vapour and rises to the upper region, where it is condensed again by the cold and so returns to the earth.*

- Several years after Aristotle's book, his pupil Theophrastus puts together a book on weather forecasting called *The Book of Signs*. Various indicators such as solar and lunar halos formed by high clouds are presented as ways to forecast the weather. The combined works of Aristotle and Theophrastus have such authority they become the main influence in the study of clouds, weather and weather forecasting for nearly 2000 years.
- 250 BC – Archimedes studies the concepts of buoyancy and the hydrostatic principle. Positive buoyancy is necessary for the formation of convective clouds (cumulus, cumulus congestus and cumulonimbus).
- 25 AD – Pomponius Mela, a geographer for the Roman empire, formalizes the climatic zone system.
- c. 80 AD – In his *Lunheng* (Critical Essays), the Han dynasty Chinese philosopher Wang Chong (27–97 AD) dispels the Chinese myth of rain coming from the heavens, and states that rain is evaporated from water on the earth into the air and forms clouds, stating that clouds condense into rain and also form dew, and says when the clothes of people in high mountains are moistened, this is because of the air-suspended rain water. However, Wang Chong supports his theory by quoting a similar one of Gongyang Gao's, the latter's commentary on the *Spring and Autumn Annals*, the Gongyang Zhuan, compiled in the 2nd century BC, showing that the Chinese conception of rain evaporating and rising to form clouds goes back much farther than Wang Chong. Wang Chong wrote:

- *As to this coming of rain from the mountains, some hold that the clouds carry the rain with them, dispersing as it is precipitated (and they are right). Clouds and rain are really the same thing. Water evaporating upwards becomes clouds, which condense into rain, or still further into dew.*

Middle Ages

- 500 AD – In around 500 AD, the Indian astronomer, mathematician, and astrologer: Varāhamihira published his work Brihat-Samhita's, which provides clear evidence that a deep knowledge of atmospheric processes existed in the Indian region.
- 7th century – The poet Kalidasa in his epic Meghaduta, mentions the date of onset of the south-west Monsoon over central India and traces the path of the monsoon clouds.
- 7th century – St. Isidore of Seville,in his work *De Rerum Natura*, writes about astronomy, cosmology and meteorology. In the chapter dedicated to Meteorology, he discusses the thunder, clouds, rainbows and wind.
- 9th century – Al-Kindi (Alkindus), an Arab naturalist, writes a treatise on meteorology entitled *Risala fi l-Illa al-Failali l-Madd wa l-Fazr* (*Treatise on the Efficient Cause of the Flow and Ebb*), in which he presents an argument on tides which "depends on the changes which take place in bodies owing to the rise and fall of temperature."

- 9th century – Al-Dinawari, a Kurdish naturalist, writes the *Kitab al-Nabat* (*Book of Plants*), in which he deals with the application of meteorology to agriculture during the Muslim Agricultural Revolution. He describes the meteorological character of the sky, the planets and constellations, the Sun and Moon, the lunar phases indicating seasons and rain, the *anwa* (heavenly bodies of rain), and atmospheric phenomena such as winds, thunder, lightning, snow, floods, valleys, rivers, lakes, wells and other sources of water.
- 10th century – Ibn Wahshiyya's *Nabatean Agriculture* discusses the weather forecasting of atmospheric changes and signs from the planetary astral alterations; signs of rain based on observation of the lunar phases, nature of thunder and lightning, direction of sunrise, behaviour of certain plants and animals, and weather forecasts based on the movement of winds; pollenized air and winds; and formation of winds and vapours.
- 1021 – Ibn al-Haytham (Alhazen) writes on the atmospheric refraction of light, the cause of morning and evening twilight. He endeavored by use of hyperbola and geometric optics to chart and formulate basic laws on atmospheric refraction. He provides the first correct definition of the twilight, discusses atmospheric refraction, shows that the twilight is due to atmospheric refraction and only begins when the Sun is 19 degrees below the horizon, and uses a complex geometric demonstration to measure the height of the Earth's

atmosphere as 52,000 *passuum* (49 miles), which is very close to the modern measurement of 50 miles.

- 1020s – Ibn al-Haytham publishes his *Risala fi l-Daw'* (*Treatise on Light*) as a supplement to his *Book of Optics*. He discusses the meteorology of the rainbow, the density of the atmosphere, and various celestial phenomena, including the eclipse, twilight and moonlight.
- 1027 – Avicenna publishes *The Book of Healing*, in which Part 2, Section 5, contains his essay on mineralogy and meteorology in six chapters: formation of mountains; the advantages of mountains in the formation of clouds; sources of water; origin of earthquakes; formation of minerals; and the diversity of earth's terrain. He also describes the structure of a meteor, and his theory on the formation of metals combined the alchemicalsulfur-mercury theory of metals (although he was critical of alchemy) with the mineralogical theories of Aristotle and Theophrastus. His scientific methodology of field observation was also original in the Earth sciences.
- Late 11th century – Abu 'Abd Allah Muhammad ibn Ma'udh, who lived in Al-Andalus, wrote a work on optics later translated into Latin as *Liber de crepisculis*, which was mistakenly attributed to Alhazen. This was a short work containing an estimation of the angle of depression of the sun at the beginning of the morning twilight and at the end of the evening twilight, and an attempt to calculate on the basis of this and other data the height of the atmospheric moisture responsible for the refraction of the sun's rays. Through his experiments, he

obtained the accurate value of 18°, which comes close to the modern value.

- 1088 – In his *Dream Pool Essays* (夢溪筆談), the Chinese scientist Shen Kuo wrote vivid descriptions of tornadoes, that rainbows were formed by the shadow of the sun in rain, occurring when the sun would shine upon it, and the curious common phenomena of the effect of lightning that, when striking a house, would merely scorch the walls a bit but completely melt to liquid all metal objects inside.
- 1121 – Al-Khazini, a Muslim scientist of Byzantine Greek descent, publishes *The Book of the Balance of Wisdom*, the first study on the hydrostatic balance.
- 13th century-St. Albert the Great is the first to propose that each drop of falling rain had the form of a small sphere, and that this form meant that the rainbow was produced by light interacting with each raindrop.
- 1267 – Roger Bacon was the first to calculate the angular size of the rainbow. He stated that the rainbow summit can not appear higher than 42 degrees above the horizon.
- 1337 – William Merle, rector of Driby, starts recording his weather diary, the oldest existing in print. The endeavour ended 1344.
- Late 13th century – Theoderic of Freiburg and Kamāl al-Dīn al-Fārisī give the first accurate explanations of the primary rainbow, simultaneously but independently. Theoderic also gives the explanation for the secondary rainbow.
- 1441 – King Sejongs son, Prince Munjong, invented the first standardized rain gauge. These were sent

throughout the Joseon Dynasty of Korea as an official tool to assess land taxes based upon a farmer's potential harvest.

- 1450 – Leone Battista Alberti developed a **swinging-plate anemometer**, and is known as the first *anemometer*.
- – Nicolas Cryfts, (Nicolas of Cusa), described the first **hair hygrometer** to measure humidity. The design was drawn by Leonardo da Vinci, referencing Cryfts design in *da Vinci's Codex Atlanticus*.
- 1483 –Yuriy Drohobych publishes *Prognostic Estimation of the year 1483* in Rome, where he reflects upon weather forecasting and that climatic conditions depended on the latitude.
- 1488 – Johannes Lichtenberger publishes the first version of his *Prognosticatio* linking weather forecasting with astrology. The paradigm was only challenged centuries later.
- 1494 – During his second voyage Christopher Columbus experiences a tropical cyclone in the Atlantic Ocean, which leads to the first written European account of a hurricane.
- 1510 – Leonhard Reynmann, astronomer of Nuremberg, publishes ″Wetterbüchlein Von warer erkanntnus des wetters″, a collection of weather lore.
- 1547 –Antonio Mizauld publishes "Le miroueer du temps, autrement dit, éphémérides perpétuelles de l'air par lesquelles sont tous les jours donez vrais signes de touts changements de temps, seulement par choses qui à tous apparoissent au cien, en l'air, sur terre & en l'eau. Le tout par petits aphorismes, & breves sentences diligemment compris" in Paris, with

detail on forecasting weather, comets and earthquakes.

17th century

1607 – Galileo Galilei constructs a thermoscope. Not only did this device measure temperature, but it represented a paradigm shift. Up to this point, heat and cold were believed to be qualities of Aristotle's elements (fire, water, air, and earth). *Note: There is some controversy about who actually built this first thermoscope. There is some evidence for this device being independently built at several different times.* This is the era of the first recorded meteorological observations. As there was no standard measurement, they were of little use until the work of Daniel Gabriel Fahrenheit and Anders Celsius in the 18th century.

- 1611 – Johannes Kepler writes the first scientific treatise on snow crystals: "Strena Seu de Nive Sexangula (A New Year's Gift of Hexagonal Snow)".
- 1620 – Francis Bacon (philosopher) analyzes the scientific method in his philosophical work; Novum Organum.
- 1643 – Evangelista Torricelli invents the **mercury barometer**.
- 1648 – Blaise Pascal rediscovers that atmospheric pressure decreases with height, and deduces that there is a vacuum above the atmosphere.
- 1654 – Ferdinando II de Medici sponsors the first *weather observing*network, that consisted of meteorological stations in Florence, Cutigliano,

Vallombrosa, Bologna, Parma, Milan, Innsbruck, Osnabrück, Paris and Warsaw. Collected data was centrally sent to Accademia del Cimento in Florence at regular time intervals.

- 1662 – Sir Christopher Wren invented the mechanical, self-emptying, **tipping bucket rain gauge**.
- 1667 – Robert Hooke builds another type of anemometer, called a **pressure-plate anemometer**.
- 1686 – Edmund Halley presents a systematic study of the trade winds and monsoons and identifies solar heating as the cause of atmospheric motions.
- – Edmund Halley establishes the relationship between barometric pressure and height above sea level.

18th century

- 1716 – Edmund Halley suggests that aurorae are caused by "magnetic effluvia" moving along the Earth's magnetic field lines.
- 1724 – Gabriel Fahrenheit creates reliable scale for measuring temperature with a mercury-type thermometer.
- 1735 – The first *ideal* explanation of global circulation was the study of the Trade winds by George Hadley.
- 1738 – Daniel Bernoulli publishes *Hydrodynamics*, initiating the kinetic theory of gases. He gave a poorly detailed equation of state, but also the basic laws for the theory of gases.

- 1742 – Anders Celsius, a Swedish astronomer, proposed the Celsius temperature scale which led to the current Celsius scale.
- 1743 – Benjamin Franklin is prevented from seeing a lunar eclipse by a hurricane, he decides that cyclones move in a contrary manner to the winds at their periphery.
- 1761 – Joseph Black discovers that ice absorbs heat without changing its temperature when melting.
- 1772 – Black's student Daniel Rutherford discovers nitrogen, which he calls *phlogisticated air*, and together they explain the results in terms of the phlogiston theory.
- 1774 – Louis Cotte is put in charge of a "medico-meteorological" network of French veterinarians and country doctors to investigate the relationship between plague and weather. The project continued until 1794.
- - Royal Society begins twice daily observations compiled by Samuel Horsley testing for the influence of winds and of the moon on the barometer readings.
- 1777 – Antoine Lavoisier discovers oxygen and develops an explanation for combustion.
- 1780 – Charles Theodor charters the first international network of meteorological observers known as "Societas Meteorologica Palatina". The project collapses in 1795.
- 1780 – James Six invents the Six's thermometer, a thermometer that records minimum and maximum temperatures. See (Six's thermometer)

- 1783 – In Lavoisier's article "Reflexions sur le phlogistique", he deprecates the phlogiston theory and proposes a caloric theory of heat.
- – First hair hygrometer demonstrated. The inventor was Horace-Bénédict de Saussure.

19th century

- 1800 – The Voltaic pile was the first modern electric battery, invented by Alessandro Volta, which led to later inventions like the telegraph.
- 1802–1803 – Luke Howard writes *On the Modification of Clouds* in which he assigns cloud types Latin names. Howard's system establishes three physical categories or *forms* based on appearance and process of formation: *cirriform* (mainly detached and wispy), *cumuliform* or convective (mostly detached and heaped, rolled, or rippled), and non-convective *stratiform* (mainly continuous layers in sheets). These are cross-classified into *lower* and *upper* levels or étages. Cumuliform clouds forming in the lower level are given the genus name cumulus from the Latin word for *heap*, while low stratiform clouds are given the genus name stratus from the Latin word for a flattened or spread out *sheet*. Cirriform clouds are identified as always upper level and given the genus name cirrus from the Latin for *hair*. From this genus name, the prefix *cirro-* is derived and attached to the names of upper level cumulus and stratus, yielding the names cirrocumulus, and cirrostratus. In addition to these individual cloud types; Howard

adds two names to designate cloud systems consisting of more than one form joined together or located in very close proximity. Cumulostratus describes large cumulus clouds blended with stratiform layers in the lower or upper levels. The term nimbus, taken from the Latin word for *rain cloud*, is given to complex systems of cirriform, cumuliform, and stratiform clouds with sufficient vertical development to produce significant precipitation, and it comes to be identified as a distinct *nimbiform* physical category.

- 1804 – Sir John Leslie observes that a matte black surface radiates heat more effectively than a polished surface, suggesting the importance of black-body radiation.
- 1806 – Francis Beaufort introduces his system for classifying wind speeds.
- 1808 – John Dalton defends caloric theory in *A New System of Chemistry* and describes how it combines with matter, especially gases; he proposes that the heat capacity of gases varies inversely with atomic weight.
- 1810 – Sir John Leslie freezes water to ice artificially.
- 1817 – Alexander von Humboldt publishes a global map of average temperature, the first global climate analysis.
- 1819 – Pierre Louis Dulong and Alexis Thérèse Petit give the Dulong-Petit law for the specific heat capacity of a crystal.
- 1820 – Heinrich Wilhelm Brandes publishes the first synoptic weather maps.

- – John Herapath develops some ideas in the kinetic theory of gases but mistakenly associates temperature with molecular momentum rather than kinetic energy; his work receives little attention other than from Joule.
- 1822 – Joseph Fourier formally introduces the use of dimensions for physical quantities in his *Theorie Analytique de la Chaleur*.
- 1824 – Sadi Carnot analyzes the efficiency of steam engines using caloric theory; he develops the notion of a reversible process and, in postulating that no such thing exists in nature, lays the foundation for the second law of thermodynamics.
- 1827 – Robert Brown discovers the Brownian motion of pollen and dye particles in water.
- 1832 – An electromagnetic telegraph was created by Baron Schilling.
- 1834 – Émile Clapeyron popularises Carnot's work through a graphical and analytic formulation.
- 1835 – Gaspard-Gustave Coriolis publishes theoretical discussions of machines with revolving parts and their efficiency, for example the efficiency of waterwheels. At the end of the 19th century, meteorologists recognized that the way the Earth's rotation is taken into account in meteorology is analogous to what Coriolis discussed: an example of Coriolis Effect.
- 1836 – An American scientist, Dr. David Alter, invented the first known American electric telegraph in Elderton, Pennsylvania, one year before the much more popular Morse telegraph was invented.

- 1837 – Samuel Morse independently developed an electrical telegraph, an alternative design that was capable of transmitting over long distances using poor quality wire. His assistant, Alfred Vail, developed the Morse code signaling alphabet with Morse. The first electric telegram using this device was sent by Morse on May 24, 1844 from the U.S. Capitol in Washington, D.C. to the B&O Railroad "outer depot" in Baltimore and sent the message:
- *What hath God wrought*
- 1839 – The *first commercial* electrical telegraph was constructed by Sir William Fothergill Cooke and entered use on the Great Western Railway. Cooke and Wheatstone patented it in May 1837 as an alarm system.
- 1840 – Elias Loomis becomes the first person known to attempt to devise a theory on frontal zones. The idea of fronts do not catch on until expanded upon by the Norwegians in the years following World War I.
- – German meteorologist Ludwig Kaemtz adds stratocumulus to Howard's canon as a mostly detached low-étage genus of *limited* convection. It is defined as having cumuliform and stratiform characteristics integrated into a single layer (in contrast to cumulostratus which is deemed to be composite in nature and can be structured into more than one layer). This eventually leads to the formal recognition of a *stratocumuliform* physical category that includes rolled and rippled clouds classified separately from the more freely convective heaped cumuliform clouds.

- 1843 – John James Waterston fully expounds the kinetic theory of gases, but is ridiculed and ignored.
- – James Prescott Joule experimentally finds the mechanical equivalent of heat.
- 1844 – Lucien Vidi invented the aneroid, from Greek meaning *without liquid*, barometer.
- 1845 – Francis Ronalds invented the first successful camera for continuous recording of the variations in meteorological parameters over time
- 1845 – Francis Ronalds invented and named the storm clock, used to monitor rapid changes in meteorological parameters during extreme events
- 1846 – Cup anemometer invented by Dr. John Thomas Romney Robinson.
- 1847 – Francis Ronalds and William Radcliffe Birt described a stable kite to make observations at altitude using self-recording instruments
- 1847 – Hermann von Helmholtz publishes a definitive statement of the conservation of energy, the first law of thermodynamics.
- – The Manchester Examiner newspaper organises the first weather reports collected by electrical means.
- 1848 – William Thomson extends the concept of absolute zero from gases to all substances.
- 1849 – Smithsonian Institution begins to establish an observation network across the United States, with 150 observers via telegraph, under the leadership of Joseph Henry.
- – William John Macquorn Rankine calculates the correct relationship between saturated vapour pressure and temperature using his *hypothesis of molecular vortices*.

- 1850 – Rankine uses his *vortex* theory to establish accurate relationships between the temperature, pressure, and density of gases, and expressions for the latent heat of evaporation of a liquid; he accurately predicts the surprising fact that the apparent specific heat of saturated steam will be negative.
- – Rudolf Clausius gives the first clear joint statement of the first and second law of thermodynamics, abandoning the caloric theory, but preserving Carnot's principle.
- 1852 – Joule and Thomson demonstrate that a rapidly expanding gas cools, later named the Joule-Thomson effect.
- 1853 – The first International Meteorological Conference was held in Brussels at the initiative of Matthew Fontaine Maury, U.S. Navy, recommending standard observing times, methods of observation and logging format for weather reports from ships at sea.
- 1854 – The French astronomer Leverrier showed that a storm in the Black Sea could be followed across Europe and would have been predictable if the telegraph had been used. A service of storm forecasts was established a year later by the Paris Observatory.
- – Rankine introduces his *thermodynamic function*, later identified as entropy.
- Mid 1850s – Emilien Renou, director of the Parc Saint-Maur and Montsouris observatories, begins work on an elaboration of Howard's classifications that would lead to the introduction during the 1870s

of a newly defined *middle*étage . Clouds in this altitude range are given the prefix *alto*- derived from the Latin word *altum* pertaining to height above the low-level clouds. This resultes in the genus name altocumulus for mid-level cumuliform and stratocumuliform types and altostratus for stratiform types in the same altitude range.

- 1856 – William Ferrel publishes his essay on the winds and the currents of the oceans.
- 1859 – James Clerk Maxwell discovers the distribution law of molecular velocities.
- 1860 – Robert FitzRoy uses the new telegraph system to gather daily observations from across England and produces the first synoptic charts. He also coined the term "weather forecast" and his were the first ever daily weather forecasts to be published in this year.
- – After establishment in 1849, 500 U.S. telegraph stations are now making weather observations and submitting them back to the Smithsonian Institution. The observations are later interrupted by the American Civil War.
- 1865 – Josef Loschmidt applies Maxwell's theory to estimate the number-density of molecules in gases, given observed gas viscosities.
- – Manila Observatory founded in the Philippines.
- 1869 – Joseph Lockyer starts the scientific journal *Nature*.
- 1869 – The New York Meteorological Observatory opens, and begins to record wind, precipitation and temperature data.

- 1870 – The US Weather Bureau is founded. Data recorded in several Midwestern cities such as Chicago begins.
- 1870 – Benito Viñes becomes the head of the Meteorological Observatory at Belen in Havana, Cuba. He develops the first observing network in Cuba and creates some of the first hurricane-related forecasts.
- 1872 – The "Oficina Meteorológica Argentina" (today "Argentinean National Weather Service") is founded.
- 1872 – Ludwig Boltzmann states the Boltzmann equation for the temporal development of distribution functions in phase space, and publishes his H-theorem.
- 1873 – International Meteorological Organization formed in Vienna.
- – United States Army Signal Corp, forerunner of the National Weather Service, issues its first hurricane warning.
- 1875 – The India Meteorological Department is established, after a tropical cyclone struck Calcutta in 1864 and monsoon failures during 1866 and 1871.
- 1876 – Josiah Willard Gibbs publishes the first of two papers (the second appears in 1878) which discuss phase equilibria, statistical ensembles, the free energy as the driving force behind chemical reactions, and chemical thermodynamics in general.
- 1880 – Philip Weilbach, secretary and librarian at the Art Academy in Copenhagen proposes and has accepted by the permanent committee of the International Meteorological Organization (IMO), a

forerunner of the present-day World Meteorological Organization (WMO), the designation of a new free-convective vertical or multi-étage genus type, cumulonimbus (heaped rain cloud). It would be distinct from cumulus and nimbus and identifiable by its often very complex structure (frequently including a cirriform top and what are now recognized as multiple accessory clouds), and its ability to produce thunder. With this addition, a canon of ten tropospheric cloud *genera* is established that comes to be officially and universally accepted. Howard's cumulostratus is not included as a distinct type, having effectively been reclassified into its component cumuliform and stratiform genus types already included in the new canon.

- 1881 – Finnish Meteorological Central Office was formed from part of Magnetic Observatory of Helsinki University.
- 1890 – US Weather Bureau is created as a civilian operation under the U.S. Department of Agriculture.
- – Otto Jesse reveals the discovery and identification of the first clouds known to form above the troposphere. He proposes the name *noctilucent* which is Latin for *night shining*. Because of the extremely high altitudes of these clouds in what is now known to be the mesosphere, they can become illuminated by the sun's rays when the sky is nearly dark after sunset and before sunrise.
- 1892 – William Henry Dines invented another kind of anemometer, called the **pressure-tube (Dines) anemometer**. His device measured the difference in

pressure arising from wind blowing in a tube versus that blowing across the tube.

- – The first mention of the term "El Niño" to refer to climate occurs when Captain Camilo Carrilo told the Geographical society congress in Lima that Peruvian sailors named the warm northerly current "El Niño" because it was most noticeable around Christmas.
- 1893 – Henrik Mohn reveals a discovery of nacreous clouds in what is now considered the stratosphere.
- 1896 – IMO publishes the first International cloud atlas.
- – Svante Arrhenius proposes carbon dioxide as a key factor to explain the ice ages.
- – H.H. Clayton proposes formalizing the division of clouds by their physical structures into cirriform, stratiform, "flocciform" (stratocumuliform) and cumuliform. With the later addition of cumulonimbiform, the idea eventually finds favor as an aid in the analysis of satellite cloud images.
- 1898 – US Weather Bureau established a hurricane warning network at Kingston, Jamaica.

20th century

- 1902 – Richard Assmann and Léon Teisserenc de Bort, two European scientists, independently discovered the stratosphere.
- - The Marconi Company issues the first routine weather forecast by means of radio to ships on sea. Weather reports from ships started 1905.

- 1903 – Max Margules publishes „Über die Energie der Stürme", an essay on the atmosphere as a three-dimensional thermodynamical machine.
- 1904 – Vilhelm Bjerknes presents the vision that forecasting the weather is feasible based on mathematical methods.
- 1905 – Australian Bureau of Meteorology established by a Meteorology Act to unify existing state meteorological services.
- 1919 – Norwegian cyclone model introduced for the first time in meteorological literature. Marks a revolution in the way the atmosphere is conceived and immediately starts leading to improved forecasts.
- - Sakuhei Fujiwhara is the first to note that hurricanes move with the larger scale flow, and later publishes a paper on the Fujiwhara effect in 1921.
- 1920 – Milutin Milanković proposes that long term climatic cycles may be due to changes in the eccentricity of the Earth's orbit and changes in the Earth's obliquity.
- 1922 – Lewis Fry Richardson organises the first numerical weather prediction experiment.
- 1923 – The oscillation effects of ENSO were first *erroneously* described by Sir Gilbert Thomas Walker from whom the Walker circulation takes its name; now an important aspect of the *Pacific ENSO* phenomenon.
- 1924 – Gilbert Walker first coined the term "Southern Oscillation".
- 1930, January 30 – Pavel Molchanov invents and launches the first radiosonde. Named "271120", it

was released 13:44 Moscow Time in Pavlovsk, USSR from the Main Geophysical Observatory, reached a height of 7.8 kilometers measuring temperature there (–40.7 °C) and sent the first aerological message to the Leningrad Weather Bureau and Moscow Central Forecast Institute.

- 1932 – A further modification of Luke Howard's cloud classification system comes when an IMC commission for the study of clouds puts forward a refined and more restricted definition of the genus nimbus which is effectively reclassified as a stratiform cloud type. It is renamed nimbostratus (flattened or spread out rain cloud) and published with the new name in the 1932 edition of the *International Atlas of Clouds and of States of the Sky*. This leaves cumulonimbus as the only nimbiform type as indicated by its root-name.
- 1933 – Victor Schauberger publishes his theories on the carbon cycle and its relationship to the weather in *Our Senseless Toil*
- 1935 – IMO decides on the 30 years normal period (1900–1930) to describe the climate.
- 1937 – The U.S. Army Air Forces Weather Service was established (redesignated in 1946 as **AWS**-Air Weather Service).
- 1938 – Guy Stewart Callendar first to propose global warming from carbon dioxide emissions.
- 1939 – Rossby waves were first identified in the atmosphere by Carl-Gustaf Arvid Rossby who explained their motion. Rossby waves are a subset of inertial waves.

- 1941 – Pulsed radar network is implemented in England during World War II. Generally during the war, operators started noticing echoes from weather elements such as rain and snow.
- 1943 – 10 years after flying into the Washington Hoover Airport on mainly instruments during the August 1933 Chesapeake-Potomac hurricane, J. B. Duckworth flies his airplane into a Gulf hurricane off the coast of Texas, proving to the military and meteorological community the utility of weather reconnaissance.
- 1944 – The Great Atlantic Hurricane is caught on radar near the Mid-Atlantic coast, the first such picture noted from the United States.
- 1947 – The Soviet Union launched its first Long Range Ballistic Rocket October 18, based on the German rocket A4 (V-2). The photographs demonstrated the immense potential of observing weather from space.
- 1948 – First correct tornado prediction by Robert C. Miller and E. J. Fawbush for tornado in Oklahoma.
- – Erik Palmén publishes his findings that hurricanes require surface water temperatures of at least 26°C (80°F) in order to form.
- 1950 – First successful numerical weather prediction experiment. Princeton University, group of Jule Gregory Charney on ENIAC.
- – Hurricanes begin to be named alphabetically with the radio alphabet.
- – **WMO** World Meteorological Organization replaces IMO under the auspice of the United Nations.

- 1953 – National Hurricane Center (NOAA) creates a system for naming hurricanes using alphabetical lists of women's names.
- 1954 – First routine real-time numerical weather forecasting. The Royal Swedish Air Force Weather Service.
- – A United States Navy rocket captures a picture of an inland tropical depression near the Texas/Mexico border, which leads to a surprise flood event in New Mexico. This convinces the government to set up a weather satellite program.
- 1955 – Norman Phillips at the Institute for Advanced Study in Princeton, New Jersey, runs first Atmospheric General Circulation Model.
- – **NSSP** National Severe Storms Project and **NHRP** National Hurricane Research Projects established. The Miami office of the United States Weather Bureau is designated the main hurricane warning center for the Atlantic Basin.
- 1957–1958 – International Geophysical Year coordinated research efforts in eleven sciences, focused on polar areas during the solar maximum.
- 1959 – The first weather satellite, Vanguard 2, was launched on February 17. It was designed to measure cloud cover, but a poor axis of rotation kept it from collecting a notable amount of useful data.
- 1960 – The first successful weather satellite, TIROS-1 (Television Infrared Observation Satellite), is launched on April 1 from Cape Canaveral, Florida by the National Aeronautics and Space Administration (NASA) with the participation of The US Army Signal Research and Development Lab, RCA, the US

Weather Bureau, and the US Naval Photographic Center. During its 78-day mission, it relays thousands of pictures showing the structure of large-scale cloud regimes, and proves that satellites can provide useful surveillance of global weather conditions from space. TIROS paves the way for the Nimbus program, whose technology and findings are the heritage of most of the Earth-observing satellites NASA and NOAA have launched since then.

- 1961 – Edward Lorenz accidentally discovers Chaos theory when working on numerical weather prediction.
- 1962 – Keith Browning and Frank Ludlam publish first detailed study of a *supercell* storm (over Wokingham, UK). Project STORMFURY begins its 10-year project of seeding hurricanes with silver iodide, attempting to weaken the cyclones.
- 1968 – A hurricane database for Atlantic hurricanes is created for NASA by Charlie Newmann and John Hope, named HURDAT.
- 1969 – Saffir–Simpson Hurricane Scale created, used to describe hurricane strength on a category range of 1 to 5. Popularized during Hurricane Gloria of 1985 by media.
- – Jacob Bjerknes described ENSO by suggesting that an anomalously warm spot in the eastern Pacific can weaken the east-west temperature difference, causing weakening in the Walker circulation and trade wind flows, which push warm water to the west.
- 1970s Weather radars are becoming more standardized and organized into networks. The

number of scanned angles was increased to get a three-dimensional view of the precipitation, which allowed studies of thunderstorms. Experiments with the Doppler effect begin.

- 1970 – **NOAA** National Oceanic and Atmospheric Administration established. Weather Bureau is renamed the National Weather Service.
- 1971 – Ted Fujita introduces the Fujita scale for rating tornadoes.
- 1974 – **AMeDAS** network, developed by Japan Meteorological Agency used for gathering regional weather data and verifying forecast performance, begun operation on November 1, the system consists of about 1,300 stations with automatic observation equipment. These stations, of which more than 1,100 are unmanned, are located at an average interval of 17 km throughout Japan.
- 1975 – The first Geostationary Operational Environmental Satellite, **GOES**, was launched into orbit. Their role and design is to aid in hurricane tracking. Also this year, Vern Dvorak develops a scheme to estimate tropical cyclone intensity from satellite imagery.
- – The first use of a General Circulation Model to study the effects of carbon dioxide doubling. Syukuro Manabe and Richard Wetherald at Princeton University.
- 1976 – The United Kingdom Department of Industry publishes a modification of the international cloud classification system adapted for satellite cloud observations. It is co-sponsored by NASA and showes a division of clouds into stratiform, cirriform,

stratocumuliform, cumuliform, and cumulonimbiform. The last of these constitutes a change in name of the earlier nimbiform type, although this earlier name and original meaning pertaining to all rain clouds can still be found in some classifications.

Major types shown here include the ten tropospheric genera that are detectable (but not always identifiable) by satellite, and several additional major types above the troposphere that were not included with the original modification. The cumulus genus includes four species that indicate vertical size and structure.

- 1980s onwards, networks of weather radars are further expanded in the developed world. Doppler weather radar is becoming gradually more common, adds velocity information.
- 1982 – The first Synoptic Flow experiment is flown around Hurricane Debby to help define the large scale atmospheric winds that steer the storm.
- 1988 – WSR-88D type weather radar implemented in the United States. Weather surveillance radar that uses several modes to detect severe weather conditions.
- 1992 – Computers first used in the United States to draw surface analyses.
- 1997 – The Pacific Decadal Oscillation was discovered by a team studying salmon production patterns at the University of Washington.
- 1998 – Improving technology and software finally allows for the digital underlying of satellite imagery, radar imagery, model data, and surface observations

improving the quality of United States Surface Analyses.

- – CAMEX3, a NASA experiment run in conjunction with NOAA's Hurricane Field Program collects detailed data sets on Hurricanes Bonnie, Danielle, and Georges.
- 1999 – Hurricane Floyd induces *fright factor* in some coastal States and causes a massive evacuation from coastal zones from northern Florida to the Carolinas. It comes ashore in North Carolina and results in nearly 80 dead and $4.5 billion in damages mostly due to extensive flooding.

21st century

- 2001 – National Weather Service begins to produce a Unified Surface Analysis, ending duplication of effort at the Tropical Prediction Center, Ocean Prediction Center, Hydrometeorological Prediction Center, as well as the National Weather Service offices in Anchorage, AK and Honolulu, HI.
- 2003 – NOAA hurricane experts issue first experimental Eastern Pacific Hurricane Outlook.
- 2004 – A record number of hurricanes strike Florida in one year, Charley, Frances, Ivan, and Jeanne.
- 2005 – A record 27 named storms occur in the Atlantic. National Hurricane Center runs out of names from its standard list and uses Greek alphabet for the first time.

- 2006 – Weather radar improved by adding common precipitation to it such as freezing rain, rain and snow mixed, and snow for the first time.
- 2007 – The Fujita scale is replaced with the Enhanced Fujita Scale for National Weather Service tornado assessments.
- 2010s – Weather radar dramatically advances with more detailed options.

Chapter 25

History of Oceanography

Early history

Humans first acquired knowledge of the waves and currents of the seas and oceans in pre-historic times. Observations on tides were recorded by Aristotle and Strabo in 384-322 BC. Early exploration of the oceans was primarily for cartography and mainly limited to its surfaces and of the animals that fishermen brought up in nets, though depth soundings by lead line were taken.

The Portuguese campaign of Atlantic navigation is the earliest example of a systematic scientific large project, sustained over many decades, studying the currents and winds of the Atlantic.

The work of Pedro Nunes (1502-1578), one of the great mathematicians, is remembered in the navigation context for the determination of the loxodromic curve: the shortest course between two points on the surface of a sphere represented onto a two-dimensional map. When he published his "Treatise of the Sphere" (1537)(mostly a commentated translation of earlier work by others) he included a treatise on geometrical and astronomic methods of navigation. There he states clearly that Portuguese navigations were not an adventurous endeavour:

"nam se fezeram indo a acertar: mas partiam os nossos mareantes muy ensinados e prouidos de estromentos e regras de astrologia e geometria que sam as cousas que os

cosmographos ham dadar apercebidas (...) e leuaua cartas muy particularmente rumadas e na ja as de que os antigos vsauam" (were not done by chance: but our seafarers departed well taught and provided with instruments and rules of astrology (astronomy) and geometry which were matters the cosmographers would provide (...) and they took charts with exact routes and no longer those used by the ancient).

His credibility rests on being personally involved in the instruction of pilots and senior seafarers from 1527 onwards by Royal appointment, along with his recognised competence as mathematician and astronomer. The main problem in navigating back from the south of the Canary Islands (or south of Boujdour) by sail alone, is due to the change in the regime of winds and currents: the North Atlantic gyre and the Equatorial counter current will push south along the northwest bulge of Africa, while the uncertain winds where the Northeast trades meet the Southeast trades (the doldrums) leave a sailing ship to the mercy of the currents. Together, prevalent current and wind make northwards progress very difficult or impossible. It was to overcome this problem, and clear the passage to India around Africa as a viable maritime trade route, that a systematic plan of exploration was devised by the Portuguese. The return route from regions south of the Canaries became the 'volta do largo' or 'volta do mar'. The 'rediscovery' of the Azores islands in 1427 is merely a reflection of the heightened strategic importance of the islands, now sitting on the return route from the western coast of Africa (sequentially called 'volta de Guiné' and 'volta da Mina'); and the references to the Sargasso Sea (also called at the time 'Mar da Baga'), to the west of the Azores, in 1436, reveals the western extent of the return route. This is necessary, under sail, to make use of the southeasterly and northeasterly winds away from the western coast of Africa, up to the northern latitudes where the westerly winds will bring the seafarers towards the western coasts of Europe.

The secrecy involving the Portuguese navigations, with the death penalty for the leaking of maps and routes, concentrated all sensitive records in the Royal Archives, completely destroyed by the Lisbon earthquake of 1775. However, the systematic nature of the Portuguese campaign, mapping the currents and winds of the Atlantic, is demonstrated by the understanding of the seasonal variations, with expeditions setting sail at different times of the year taking different routes to take account of seasonal predominate winds. This happens from as early as late 15th century and early 16th: Bartolomeu Dias followed the African coast on his way south in August 1487, while Vasco da Gama would take an open sea route from the latitude of Sierra Leone, spending 3 months in the open sea of the South Atlantic to profit from the southwards deflection of the southwesterly on the Brazilian side (and the Brazilian current going southward) - Gama departed on July 1497); and Pedro Alvares Cabral, departing March 1500) took an even larger arch to the west, from the latitude of Cape Verde, thus avoiding the summer monsoon (which would have blocked the route taken by Gama at the time he set sail). Furthermore, there were systematic expeditions pushing into the western Northern Atlantic (Teive, 1454; Vogado, 1462; Teles, 1474; Ulmo, 1486). The documents relating to the supplying of ships, and the ordering of sun declination tables for the southern Atlantic for as early as 1493–1496, all suggest a well planned and systematic activity happening during the decade long period between Bartolomeu Dias finding the southern tip of Africa, and Gama's departure; additionally, there are indications of further travels by Bartolomeu Dias in the area. The most significant consequence of this systematised knowledge was the negotiation of the Treaty of Tordesillas in 1494, moving the line of demarcation 270 leagues to the west (from 100 to 370 leagues west of the Azores), bringing what is now Brazil into the Portuguese area of domination. The knowledge gathered from open sea exploration allowed for the well documented extended periods of sail without sight of land, not by accident but as pre-determined planned route; for example, 30 days for Bartolomeu Dias culminating on Mossel Bay, the 3 months Gama spend on the Southern Atlantic to use the Brazil current (southward), or the 29 days Cabral took from Cape Verde up to landing in Monte Pascoal, Brazil.

The Danish expedition to Arabia 1761-67 can be said to be the world's first oceanographic expedition, as the ship Grønland had on board a group of scientists, including naturalist Peter Forsskål, who was assigned an explicit task by the king, Frederik V, to study and describe the marine life in the open sea, including finding the cause of mareel, or milky seas. For this purpose the expedition was equipped with nets and scrapers, specifically designed to collect samples from the open waters and the bottom at great depth.

Although Juan Ponce de León in 1513 first identified the Gulf Stream, and the current was well known to mariners, Benjamin Franklin made the first scientific study of it and gave it its name. Franklin measured water temperatures during several Atlantic crossings and correctly explained the Gulf Stream's cause. Franklin and Timothy Folger printed the first map of the Gulf Stream in 1769–1770.

Information on the currents of the Pacific Ocean was gathered by explorers of the late 18th century, including James Cook and Louis Antoine de Bougainville. James Rennell wrote the first scientific textbooks on oceanography, detailing the current flows of the Atlantic and Indian oceans. During a voyage around the Cape of Good Hope in 1777, he mapped *"the banks and currents at the Lagullas"*. He was also the first to understand the nature of the intermittent current near the Isles of Scilly, (now known as Rennell's Current).

Sir James Clark Ross took the first modern sounding in deep sea in 1840, and Charles Darwin published a paper on reefs and the formation of atolls as a result of the second voyage of HMS *Beagle* in 1831–1836. Robert FitzRoy published a four-volume report of *Beagle*'s three voyages. In 1841–1842 Edward Forbes undertook dredging in the Aegean Sea that founded marine ecology.

The first superintendent of the United States Naval Observatory (1842–1861), Matthew Fontaine Maury devoted his time to the study of marine meteorology, navigation, and charting prevailing winds and currents. His 1855 textbook *Physical Geography of the Sea* was one of the first comprehensive oceanography studies. Many nations sent oceanographic observations to Maury at the Naval Observatory, where he and his colleagues evaluated the information and distributed the results worldwide.

Modern oceanography

- Knowledge of the oceans remained confined to the topmost few fathoms of the water and a small amount of the bottom, mainly in shallow areas. Almost nothing was known of the ocean depths. The British Royal Navy's efforts to chart all of the world's coastlines in the mid-19th century reinforced the vague idea that most of the ocean was very deep, although little more was known. As exploration ignited both popular and scientific interest in the polar regions and Africa, so too did the mysteries of the unexplored oceans.

The seminal event in the founding of the modern science of oceanography was the 1872–1876 *Challenger* expedition. As the first true oceanographic cruise, this expedition laid the groundwork for an entire academic and research discipline. In response to a recommendation from the Royal Society, the British Government announced in 1871 an expedition to explore world's oceans and conduct appropriate scientific investigation. Charles Wyville Thompson and Sir John Murray launched the *Challenger* expedition. *Challenger*, leased from the Royal Navy, was modified for scientific work and equipped with separate laboratories for natural history and chemistry. Under the scientific supervision of Thomson, *Challenger* travelled nearly 70,000 nautical miles (130,000 km) surveying and exploring. On her journey circumnavigating the globe, 492 deep sea soundings, 133 bottom dredges, 151 open water trawls and 263 serial water temperature observations were taken. Around 4,700 new species of marine life were discovered. The result was the *Report Of The Scientific Results* *of the Exploring Voyage of H.M.S. Challenger during the years 1873–76*. Murray, who supervised the publication, described the report as "the greatest advance in the knowledge of our planet since the celebrated discoveries of the fifteenth and sixteenth centuries". He went on to found the academic discipline of oceanography at the University of Edinburgh, which remained the centre for oceanographic research well into the 20th century. Murray was the first to study marine trenches and in particular the Mid-Atlantic Ridge, and map the sedimentary deposits in the oceans. He tried to map out the world's ocean currents based on salinity and temperature observations, and was the first to correctly understand the nature of coral reef development.

In the late 19th century, other Western nations also sent out scientific expeditions (as did private individuals and institutions). The first purpose built oceanographic ship, *Albatros*, was built in 1882. In 1893, Fridtjof Nansen allowed his ship, *Fram*, to be frozen in the Arctic ice. This enabled him to obtain oceanographic, meteorological and astronomical data at a stationary spot over an extended period.

In 1881 the geographer John Francon Williams published a seminal book, *Geography of the Oceans*. Between 1907 and 1911 Otto Krümmel published the *Handbuch der Ozeanographie*, which became influential in awakening public interest in oceanography. The four-month 1910 North Atlantic expedition headed by John Murray and Johan Hjort was the most ambitious research oceanographic and marine zoological project ever mounted until then, and led to the classic 1912 book *The Depths of the Ocean*.

The first acoustic measurement of sea depth was made in 1914. Between 1925 and 1927 the "Meteor" expedition gathered 70,000 ocean depth measurements using an echo sounder, surveying the Mid-Atlantic Ridge.

In 1934, Easter Ellen Cupp, the first woman to have earned a PhD (at Scripps) in the United States, completed a major work on diatoms that remained the standard taxonomy in the field until well after her death in 1999. In 1940, Cupp was let go from her position at Scripps. Sverdrup specifically commended Cupp as a conscientious and industrious worker and commented that his decision was no reflection on her ability as a scientist. Sverdrup used the instructor billet vacated by Cupp to employ Marston Sargent,a biologist studying marine algae, which was not a new research program at Scripps. Financial pressures did not prevent Sverdrup from retaining the services of two other young post-doctoral students, Walter Munk and Roger Revelle. Cupp's partner, Dorothy Rosenbury, found her a position teaching high school, where she remained for the rest of her career. (Russell, 2000)

Sverdrup, Johnson and Fleming published *The Oceans* in 1942, which was a major landmark. *The Sea* (in three volumes, covering physical oceanography, seawater and geology) edited by M.N. Hill was published in 1962, while Rhodes Fairbridge's *Encyclopedia of Oceanography* was published in 1966.

The Great Global Rift, running along the Mid Atlantic Ridge, was discovered by Maurice Ewing and Bruce Heezen in 1953 and mapped by Heezen and Marie Tharp using bathymetric data; in 1954 a mountain range under the Arctic Ocean was found by the Arctic Institute of the USSR. The theory of seafloor spreading was developed in 1960 by Harry Hammond Hess. The Ocean Drilling Program started in 1966. Deep-sea vents were discovered in 1977 by Jack Corliss and Robert Ballard in the submersible DSV *Alvin*.

In the 1950s, Auguste Piccard invented the bathyscaphe and used the bathyscaphe*Trieste* to investigate the ocean's depths. The United States nuclear submarine*Nautilus* made the first journey under the ice to the North Pole in 1958. In 1962 the FLIP (Floating Instrument Platform), a 355-foot (108 m) spar buoy, was first deployed.

In 1968, Tanya Atwater led the first all-woman oceanographic expedition. Until that time, gender policies restricted women oceanographers from participating in voyages to a significant extent.

From the 1970s, there has been much emphasis on the application of large scale computers to oceanography to allow numerical predictions of ocean conditions and as a part of overall environmental change prediction. Early techniques included analog computers (such as the Ishiguro Storm Surge Computer) generally now replaced by numerical methods (eg SLOSH.) An oceanographic buoy array was established in the Pacific to allow prediction of El Niño events.

1990 saw the start of the World Ocean Circulation Experiment (WOCE) which continued until 2002. Geosat seafloor mapping data became available in 1995.

In recent years studies advanced particular knowledge on ocean acidification, ocean heat content, ocean currents, the El Niño phenomenon, mapping of methane hydrate deposits, the carbon cycle, coastal erosion, weathering and climate feedbacks in regards to climate change interactions.

Study of the oceans is linked to understanding global climate changes, potential global warming and related biosphere concerns. The atmosphere and ocean are linked because of evaporation and precipitation as well as thermal flux (and solar insolation). Wind stress is a major driver of ocean currents while the ocean is a sink for atmospheric carbon dioxide. All these factors relate to the ocean's biogeochemical setup.

Further understanding of the worlds oceans permit scientists to better decide weather changes which in addition guides to a more reliable utilization of earths resources.

Chapter 26

History of Physics

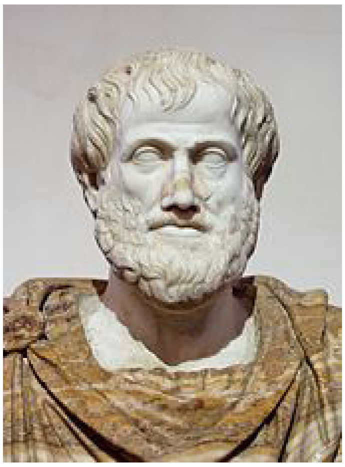
Physics is a branch of science whose primary objects of study are matter and energy. Discoveries of physics find applications throughout the natural sciences and in technology. Physics today may be divided loosely into classical physics and modern physics.

Ancient history

Elements of what became physics were drawn primarily from the fields of astronomy, optics, and mechanics, which were methodologically united through the study of geometry. These mathematical disciplines began in antiquity with the Babylonians and with Hellenistic writers such as Archimedes and Ptolemy. Ancient philosophy, meanwhile – including what was called "physics"

Greek concept

The move towards a rational understanding of nature began at least since the Archaic period in Greece (650–480 BCE) with the Pre-Socratic philosophers. The philosopher Thales of Miletus (7th and 6th centuries BCE), dubbed "the Father of Science" for refusing to accept various supernatural, religious or mythological explanations for natural phenomena, proclaimed that every event had a natural cause. Thales also made advancements in 580 BCE by suggesting that water is the basic element, experimenting with the attraction between magnets and rubbed amber and formulating the first recorded cosmologies. Anaximander, famous for his proto-evolutionary theory, ., a substance called *apeiron* was the building block of all matter. Around 500 BCE, Heraclitus proposed that the only basic law governing the Universe was the principle of change and that nothing remains in the same state indefinitely. This observation made him one of the first scholars in ancient physics to address the role of time in the universe, a key and sometimes contentious concept in modern and present-day physics.



During the classical period in Greece (6th, 5th and 4th centuries BCE) and in Hellenistic times, natural philosophy slowly developed into an exciting and contentious field of study. Aristotle (Greek: □ριστοτέλης, *Aristotélēs*) (384 – 322 BCE), a student of Plato, promoted the concept that observation of physical phenomena could ultimately lead to the discovery of the natural laws governing them. Aristotle's writings cover physics, metaphysics, poetry, theater, music, logic, rhetoric, linguistics, politics, government, ethics, biology and zoology. He wrote the first work which refers to that line of study as "Physics" – in the 4th century BCE, Aristotle founded the system known as Aristotelian physics. He attempted to explain ideas such as motion (and gravity) with the theory of four elements. Aristotle believed that all matter was made up of aether, or some combination of four elements: earth, water, air, and fire. According to Aristotle, these four terrestrial elements are capable of inter-transformation and move toward their natural place, so a stone falls downward toward the center of the cosmos, but flames rise upward toward the circumference. Eventually, Aristotelian physics became enormously popular for many centuries in Europe, informing the scientific and scholastic developments of the Middle Ages. It remained the mainstream scientific paradigm in Europe until the time of Galileo Galilei and Isaac Newton.

Early in Classical Greece, knowledge that the Earth is spherical ("round") was common. Around 240 BCE, as the result of a seminal experiment, Eratosthenes (276–194 BCE) accurately estimated its circumference. In contrast to Aristotle's geocentric views, Aristarchus of Samos (Greek: □ρίσταρχος; c.310 – c.230 BCE) presented an explicit argument for a heliocentric model of the Solar system, i.e. for placing the Sun, not the Earth, at its centre. Seleucus of Seleucia, a follower of Aristarchus' heliocentric theory, stated that the Earth rotated around its own axis, which, in turn, revolved around the Sun. Though the arguments he used were lost, Plutarch stated that Seleucus was the first to prove the heliocentric system through reasoning.

In the 3rd century BCE, the Greek mathematician Archimedes of Syracuse (Greek: Ἀρχιμήδης (287–212 BCE) – generally considered to be the greatest mathematician of antiquity and one of the greatest of all time – laid the foundations of hydrostatics, statics and calculated the underlying mathematics of the lever. A leading scientist of classical antiquity, Archimedes also developed elaborate systems of pulleys to move large objects with a minimum of effort. The Archimedes' screw underpins modern hydroengineering, and his machines of war helped to hold back the armies of Rome in the First Punic War. Archimedes even tore apart the arguments of Aristotle and his metaphysics, pointing out that it was impossible to separate mathematics and nature and proved it by converting mathematical theories into practical inventions. Furthermore, in his work *On Floating Bodies*, around 250 BCE, Archimedes developed the law of buoyancy, also known as Archimedes' principle. In mathematics, Archimedes used the method of exhaustion to calculate the area under the arc of a parabola with the summation of an infinite series, and gave a remarkably accurate approximation of pi. He also defined the spiral bearing his name, formulae for the volumes of surfaces of revolution and an ingenious system for expressing very large numbers. He also developed the principles of equilibrium states and centers of gravity, ideas that would influence the well known scholars, Galileo, and Newton.

Hipparchus (190–120 BCE), focusing on astronomy and mathematics, used sophisticated geometrical techniques to map the motion of the stars and planets, even predicting the times that Solar eclipses would happen. In addition, he added calculations of the distance of the Sun and Moon from the Earth, based upon his improvements to the observational instruments used at that time. Another of the most famous of the early physicists was Ptolemy (90–168 CE), one of the leading minds during the time of the Roman Empire. Ptolemy was the author of several scientific treatises, at least three of which were of continuing importance to later Islamic and European science. The first is the astronomical treatise now known as the *Almagest* (in Greek, ἩΜεγάληΣύνταξις, "The Great Treatise", originally ΜαθηματικὴΣύνταξις, "Mathematical Treatise"). The second is the *Geography*, which is a thorough discussion of the geographic knowledge of the Greco-Roman world.

Much of the accumulated knowledge of the ancient world was lost. Even of the works of the better known thinkers, few fragments survived. Although he wrote at least fourteen books, almost nothing of Hipparchus' direct work survived. Of the 150 reputed Aristotelian works, only 30 exist, and some of those are "little more than lecture notes".

India and China

- Important physical and mathematical traditions also existed in ancient Chinese and Indian sciences.

In Indian philosophy, Maharishi Kanada was the first to systematically develop a theory of atomism around 200 BCE though some authors have allotted him an earlier era in the 6th century BCE. It was further elaborated by the Buddhist atomists Dharmakirti and Dignāga during the 1st millennium CE. Pakudha Kaccayana, a 6th-century BCE Indian philosopher and contemporary of Gautama Buddha, had also propounded ideas about the atomic constitution of the material world. These philosophers believed that other elements (except ether) were physically palpable and hence comprised minuscule particles of matter. The last minuscule particle of matter that could not be subdivided further was termed

Parmanu. These philosophers considered the atom to be indestructible and hence eternal. The Buddhists thought atoms to be minute objects unable to be seen to the naked eye that come into being and vanish in an instant. The Vaisheshika school of philosophers believed that an atom was a mere point in space. It was also first to depict relations between motion and force applied. Indian theories about the atom are greatly abstract and enmeshed in philosophy as they were based on logic and not on personal experience or experimentation. In Indian astronomy, Aryabhata's *Aryabhatiya* (499 CE) proposed the Earth's rotation, while Nilakantha Somayaji (1444–1544) of the Kerala school of astronomy and mathematics proposed a semi-heliocentric model resembling the Tychonic system.

The study of magnetism in Ancient China dates back to the 4th century BCE. (in the *Book of the Devil Valley Master*), A main contributor to this field was Shen Kuo (1031–1095), a polymath and statesman who was the first to describe the magnetic-needle compass used for navigation, as well as establishing the concept of true north. In optics, Shen Kuo independently developed a camera obscura.

Islamic world

In the 7th to 15th centuries, scientific progress occurred in the Muslim world. Many classic works in Indian, Assyrian, Sassanian (Persian) and Greek, including the works of Aristotle, were translated into Arabic. Important contributions were made by Ibn al-Haytham (965–1040), an Arab scientist, considered to be a founder of modern optics. Ptolemy and Aristotle theorised that light either shone from the eye to illuminate objects or that "forms" emanated from objects themselves, whereas al-Haytham (known by the Latin name "Alhazen") suggested that light travels to the eye in rays from different points on an object. The works of Ibn al-Haytham and Abū Rayhān Bīrūnī (973–1050), a Persian scientist, eventually passed on to Western Europe where they were studied by scholars such as Roger Bacon and Witelo.

Ibn al-Haytham and Biruni were early proponents of the scientific method. Ibn al-Haytham is considered to be the "father of the modern scientific method" due to his emphasis on experimental data and reproducibility of its results. The earliest methodical approach to experiments in the modern sense is visible in the works of Ibn al-Haytham, who introduced an inductive-experimental method for achieving results. Bīrūnī introduced early scientific methods for several different fields of inquiry during the 1020s and 1030s, including an early experimental method for mechanics. Biruni's methodology resembled the modern scientific method, particularly in his emphasis on repeated experimentation.

Ibn Sīnā (980–1037), known as "Avicenna", was a polymath from Bukhara (in present-day Uzbekistan) responsible for important contributions to physics, optics, philosophy and medicine. He published his theory of motion in *Book of Healing* (1020), where he argued that an impetus is imparted to a projectile by the thrower, and believed that it was a temporary virtue that would decline even in a vacuum. He viewed it as persistent, requiring external forces such as air resistance to dissipate it. Ibn Sina made a distinction between 'force' and 'inclination' (called "mayl"), and argued that an object gained mayl when the object is in opposition to its natural motion. He concluded that continuation of motion is attributed to the inclination that is transferred to the object, and that object will be in motion until the mayl is spent. He also claimed that projectile in a vacuum would not stop unless it is acted upon. This conception of motion is consistent with Newton's first law of motion, inertia, which states that an object in motion will stay in motion unless it is acted on by an external force. This idea which dissented from the Aristotelian view was later described as "impetus" by John Buridan, who was influenced by Ibn Sina's *Book of Healing*.

Hibat Allah Abu'l-Barakat al-Baghdaadi (c. 1080-1165) adopted and modified Ibn Sina's theory on projectile motion. In his *Kitab al-Mu'tabar*, Abu'l-Barakat stated that the mover imparts a violent inclination (*mayl qasri*) on the moved and that this diminishes as the moving object distances itself from the mover. He also proposed an explanation of the acceleration of falling bodies by the accumulation of successive increments of power with successive increments of velocity. According to Shlomo Pines, al-Baghdaadi's theory of motion was "the oldest negation of Aristotle's fundamental dynamic law [namely, that a constant force produces a uniform motion], [and is thus an] anticipation in a vague fashion of the fundamental law of classical mechanics [namely, that a force applied continuously produces acceleration]." Jean Buridan and Albert of Saxony later referred to Abu'l-Barakat in explaining that the acceleration of a falling body is a result of its increasing impetus.

Ibn Bajjah (c. 1085–1138), known as "Avempace" in Europe, proposed that for every force there is always a reaction force. Ibn Bajjah was a critic of Ptolemy and he worked on creating a new theory of velocity to replace the one theorized by Aristotle.

Two future philosophers supported the theories Avempace created, known as Avempacean dynamics. These philosophers were Thomas Aquinas, a Catholic priest, and John Duns Scotus. Galileo went on to adopt Avempace's formula "that the velocity of a given object is the difference of the motive power of that object and the resistance of the medium of motion".

Nasir al-Din al-Tusi (1201–1274), a Persian astronomer and mathematician who died in Baghdad introduced the Tusi couple. Copernicus later drew heavily on the work of al-Din al-Tusi and his students, but without acknowledgment.

Medieval Europe

Awareness of ancient works re-entered the West through translations from Arabic to Latin. Their re-introduction, combined with Judeo-Islamic theological commentaries, had a great influence on Medieval philosophers such as Thomas Aquinas. Scholastic European scholars, who sought to reconcile the philosophy of the ancient classical philosophers with Christian theology, proclaimed Aristotle the greatest thinker of the ancient world. In cases where they didn't directly contradict the Bible, Aristotelian physics became the foundation for the physical explanations of the European Churches. Quantification became a core element of medieval physics. Based on Aristotelian physics, Scholastic physics described things as moving according to their essential nature. Celestial objects were described as moving in circles, because perfect circular motion was considered an innate property of objects that existed in the uncorrupted realm of the celestial spheres. The theory of impetus, the ancestor to the concepts of inertia and momentum, was developed along similar lines by medieval philosophers such as John Philoponus and Jean Buridan. Motions below the lunar sphere were seen as imperfect, and thus could not be expected to exhibit consistent motion. More idealized motion in the "sublunary" realm could only be achieved through artifice, and prior to the 17th century, many did not view artificial experiments as a valid means of learning about the natural world. Physical explanations in the sublunary realm revolved around tendencies. Stones contained the element earth, and earthly objects tended to move in a straight line toward the centre of the earth (and the universe in the Aristotelian geocentric view) unless otherwise prevented from doing so.

Scientific revolution

During the 16th and 17th centuries, a large advancement of scientific progress known as the Scientific revolution took place in Europe. Dissatisfaction with older philosophical approaches had begun earlier and had produced other changes in society, such as the Protestant Reformation, but the revolution in science began when natural philosophers began to mount a sustained attack on the Scholastic philosophical programme and supposed that mathematical descriptive schemes adopted from such fields as mechanics and astronomy could actually yield universally valid characterizations of motion and other concepts.

Nicolaus Copernicus

A breakthrough in astronomy was made by Polish astronomer Nicolaus Copernicus (1473–1543) when, in 1543, he gave strong arguments for the heliocentric model of the Solar system, ostensibly as a means to render tables charting planetary motion more accurate and to simplify their production. In heliocentric models of the Solar system, the Earth orbits the Sun along with other bodies in Earth's galaxy, a contradiction according to the Greek-Egyptian astronomer Ptolemy (2nd century CE; see above), whose system placed the Earth at the center of the Universe and had been accepted for over 1,400 years. The Greek astronomer Aristarchus of Samos (c.310 – c.230 BCE) had suggested that the Earth revolves around the Sun, but Copernicus' reasoning led to lasting general acceptance of this "revolutionary" idea. Copernicus' book presenting the theory (*De revolutionibus orbium coelestium*, "On the Revolutions of the Celestial Spheres") was published just before his death in 1543 and, as it is now generally considered to mark the beginning of modern astronomy, is also considered to mark the beginning of the Scientific revolution. Copernicus' new perspective, along with the accurate observations made by Tycho Brahe, enabled German astronomer Johannes Kepler (1571–1630) to formulate his laws regarding planetary motion that remain in use today.

Galileo Galilei

The Italian mathematician, astronomer, and physicist Galileo Galilei (1564–1642) was famous for his support for Copernicanism, his astronomical discoveries, empirical experiments and his improvement of the telescope. As a mathematician, Galileo's role in the university culture of his era was subordinated to the three major topics of study: law, medicine, and theology (which was closely allied to philosophy). Galileo, however, felt that the descriptive content of the technical disciplines warranted philosophical interest, particularly because mathematical analysis of astronomical observations – notably, Copernicus' analysis of the relative motions of the Sun, Earth, Moon, and planets – indicated that philosophers' statements about the nature of the universe could be shown to be in error. Galileo also performed mechanical experiments, insisting that motion itself – regardless of whether it was produced "naturally" or "artificially" (i.e. deliberately) – had universally consistent characteristics that could be described mathematically.

Galileo's early studies at the University of Pisa were in medicine, but he was soon drawn to mathematics and physics. At 19, he discovered (and, subsequently, verified) the isochronal nature of the pendulum when, using his pulse, he timed the oscillations of a swinging lamp in Pisa's cathedral and found that it remained the same for each swing regardless of the swing's amplitude. He soon became known through his invention of a hydrostatic balance and for his treatise on the center of gravity of solid bodies. While teaching at the University of Pisa (1589–92), he initiated his experiments concerning the laws of bodies in motion that brought results so contradictory to the accepted teachings of Aristotle that strong antagonism was aroused. He found that bodies do not fall with velocities proportional to their weights. The famous story in which Galileo is said to have dropped weights from the Leaning Tower of Pisa is apocryphal, but he did find that the path of a projectile is a parabola and is credited with conclusions that anticipated Newton's laws of motion (e.g. the notion of inertia). Among these is what is now called Galilean relativity, the first precisely formulated statement about properties of space and time outside three-dimensional geometry.

Galileo has been called the "father of modern observational astronomy", the "father of modern physics", the "father of science", and "the father of modern science". According to Stephen Hawking, "Galileo, perhaps more than any other single person, was responsible for the birth of modern science." As religious orthodoxy decreed a geocentric or Tychonic understanding of the Solar system, Galileo's support for heliocentrism provoked controversy and he was tried by the Inquisition. Found "vehemently suspect of heresy", he was forced to recant and spent the rest of his life under house arrest.

The contributions that Galileo made to observational astronomy include the telescopic confirmation of the phases of Venus; his discovery, in 1609, of Jupiter's four largest moons (subsequently given the collective name of the "Galilean moons"); and the observation and analysis of sunspots. Galileo also pursued applied science and technology, inventing, among other instruments, a military compass. His discovery of the Jovian moons was published in 1610 and enabled him to obtain the position of mathematician and philosopher to the Medici court. As such, he was expected to engage in debates with philosophers in the Aristotelian tradition and received a large audience for his own publications such as the *Discourses and Mathematical Demonstrations Concerning Two New Sciences* (published abroad following his arrest for the publication of *Dialogue Concerning the Two Chief World Systems*) and *The Assayer*. Galileo's interest in experimenting with and formulating mathematical descriptions of motion established experimentation as an integral part of natural philosophy. This tradition, combining with the non-mathematical emphasis on the collection of "experimental histories" by philosophical reformists such as William Gilbert and Francis Bacon, drew a significant following in the years leading up to and following Galileo's death, including Evangelista Torricelli and the participants in the Accademia del Cimento in Italy; Marin Mersenne and Blaise Pascal in France; Christiaan Huygens in the Netherlands; and Robert Hooke and Robert Boyle in England.

René Descartes

The French philosopher René Descartes (1596–1650) was well-connected to, and influential within, the experimental philosophy networks of the day. Descartes had a more ambitious agenda, however, which was geared toward replacing the Scholastic philosophical tradition altogether. Questioning the reality interpreted through the senses, Descartes sought to re-establish philosophical explanatory schemes by reducing all perceived phenomena to being attributable to the motion of an invisible sea of "corpuscles". (Notably, he reserved human thought and God from his scheme, holding these to be separate from the physical universe). In proposing this philosophical framework, Descartes supposed that different kinds of motion, such as that of planets versus that of terrestrial objects, were not fundamentally different, but were merely different manifestations of an endless chain of corpuscular motions obeying universal principles. Particularly influential were his explanations for circular astronomical motions in terms of the vortex motion of corpuscles in space (Descartes argued, in accord with the beliefs, if not the methods, of the Scholastics, that a vacuum could not exist), and his explanation of gravity in terms of corpuscles pushing objects downward.

Descartes, like Galileo, was convinced of the importance of mathematical explanation, and he and his followers were key figures in the development of mathematics and geometry in the 17th century. Cartesian mathematical descriptions of motion held that all mathematical formulations had to be justifiable in terms of direct physical action, a position held by Huygens and the German philosopher Gottfried Leibniz, who, while following in the Cartesian tradition, developed his own philosophical alternative to Scholasticism, which he outlined in his 1714 work, *The Monadology*. Descartes has been dubbed the 'Father of Modern Philosophy', and much subsequent Western philosophy is a response to his writings, which are studied closely to this day. In particular, his *Meditations on First Philosophy* continues to be a standard text at most university philosophy departments. Descartes' influence in mathematics is equally apparent; the Cartesian coordinate system — allowing algebraic equations to be expressed as geometric shapes in a two-dimensional coordinate system — was named after him. He is credited as the father of analytical geometry, the bridge between algebra and geometry, important to the discovery of calculus and analysis.

Isaac Newton

The late 17th and early 18th centuries saw the achievements of Cambridge University physicist and mathematician Sir Isaac Newton (1642-1727). Newton, a fellow of the Royal Society of England, combined his own discoveries in mechanics and astronomy to earlier ones to create a single system for describing the workings of the universe. Newton formulated three laws of motion which formulated the relationship between motion and objects and also the law of universal gravitation, the latter of which could be used to explain the behavior not only of falling bodies on the earth but also planets and other celestial bodies. To arrive at his results, Newton invented one form of an entirely new branch of mathematics: calculus (also invented independently by Gottfried Leibniz), which was to become an essential tool in much of the later development in most branches of physics. Newton's findings were set forth in his *Philosophiæ Naturalis Principia Mathematica* ("Mathematical Principles of Natural Philosophy"), the publication of which in 1687 marked the beginning of the modern period of mechanics and astronomy.

Newton was able to refute the Cartesian mechanical tradition that all motions should be explained with respect to the immediate force exerted by corpuscles. Using his three laws of motion and law of universal gravitation, Newton removed the idea that objects followed paths determined by natural shapes and instead demonstrated that not only regularly observed paths, but all the future motions of any body could be deduced mathematically based on knowledge of their existing motion, their mass, and the forces acting upon them. However, observed celestial motions did not precisely conform to a Newtonian treatment, and Newton, who was also deeply interested in theology, imagined that God intervened to ensure the continued stability of the solar system.

Newton's principles (but not his mathematical treatments) proved controversial with Continental philosophers, who found his lack of metaphysical explanation for movement and gravitation philosophically unacceptable. Beginning around 1700, a bitter rift opened between the Continental and British philosophical traditions, which were stoked by heated, ongoing, and viciously personal disputes between the followers of Newton and Leibniz concerning priority over the analytical techniques of calculus, which each had developed independently. Initially, the Cartesian and Leibnizian traditions prevailed on the Continent (leading to the dominance of the Leibnizian calculus notation everywhere except Britain). Newton himself remained privately disturbed at the lack of a philosophical understanding of gravitation while insisting in his writings that none was necessary to infer its reality. As the 18th century progressed, Continental natural philosophers increasingly accepted the Newtonians' willingness to forgo ontological metaphysical explanations for mathematically described motions.

Newton built the first functioning reflecting telescope and developed a theory of color, published in *Opticks*, based on the observation that a prism decomposes white light into the many colours forming the visible spectrum. While Newton explained light as being composed of tiny particles, a rival theory of light which explained its behavior in terms of waves was presented in 1690 by Christiaan Huygens. However, the belief in the mechanistic philosophy coupled with Newton's reputation meant that the wave theory saw relatively little support until the 19th century. Newton also formulated an empirical law of cooling, studied the speed of sound, investigated power series, demonstrated the generalised binomial theorem and developed a method for approximating the roots of a function. His work on infinite series was inspired by Simon Stevin's decimals. Most importantly, Newton showed that the motions of objects on Earth and of celestial bodies are governed by the same set of natural laws, which were neither capricious nor malevolent. By demonstrating the consistency between Kepler's laws of planetary motion and his own theory of gravitation, Newton also removed the last doubts about heliocentrism. By bringing together all the ideas set forth during the Scientific revolution, Newton effectively established the foundation for modern society in mathematics and science.

Other achievements

Other branches of physics also received attention during the period of the Scientific revolution. William Gilbert, court physician to Queen Elizabeth I, published an important work on magnetism in 1600, describing how the earth itself behaves like a giant magnet. Robert Boyle (1627–91) studied the behavior of gases enclosed in a chamber and formulated the gas law named for him; he also contributed to physiology and to the founding of modern chemistry. Another important factor in the scientific revolution was the rise of learned societies and academies in various countries. The earliest of these were in Italy and Germany and were short-lived. More influential were the Royal Society of England (1660) and the Academy of Sciences in France (1666). The former was a private institution in London and included such scientists as John Wallis, William Brouncker, Thomas Sydenham, John Mayow, and Christopher Wren (who contributed not only to architecture but also to astronomy and anatomy); the latter, in Paris, was a government institution and included as a foreign member the Dutchman Huygens. In the 18th century, important royal academies were established at Berlin (1700) and at St. Petersburg (1724). The societies and academies provided the principal opportunities for the publication and discussion of scientific results during and after the scientific revolution. In 1690, James Bernoulli showed that the cycloid is the solution to the tautochrone problem; and the following year, in 1691, Johann Bernoulli showed that a chain freely suspended from two points will form a catenary, the curve with the lowest possible center of gravity available to any chain hung between two fixed points. He then showed, in 1696, that the cycloid is the solution to the brachistochrone problem.

Early thermodynamics

A precursor of the engine was designed by the German scientist Otto von Guericke who, in 1650, designed and built the world's first vacuum pump and created the world's first ever vacuum known as the Magdeburg hemispheres experiment. He was driven to make a vacuum to disprove Aristotle's long-held supposition that 'Nature abhors a vacuum'. Shortly thereafter, Irish physicist and chemist Boyle had learned of Guericke's designs and in 1656, in coordination with English scientist Robert Hooke, built an air pump. Using this pump, Boyle and Hooke noticed the pressure-volume correlation for a gas: $PV = k$, where P is pressure, V is volume and k is a constant: this relationship is known as Boyle's Law. In that time, air was assumed to be a system of motionless particles, and not interpreted as a system of moving molecules. The concept of thermal motion came two centuries later. Therefore, Boyle's publication in 1660 speaks about a mechanical concept: the air spring. Later, after the invention of the thermometer, the property temperature could be quantified. This tool gave Gay-Lussac the opportunity to derive his law, which led shortly later to the ideal gas law. But, already before the establishment of the ideal gas law, an associate of Boyle's named Denis Papin built in 1679 a bone digester, which is a closed vessel with a tightly fitting lid that confines steam until a high pressure is generated.

Later designs implemented a steam release valve to keep the machine from exploding. By watching the valve rhythmically move up and down, Papin conceived of the idea of a piston and cylinder engine. He did not however follow through with his design. Nevertheless, in 1697, based on Papin's designs, engineer Thomas Savery built the first engine. Although these early engines were crude and inefficient, they attracted the attention of the leading scientists of the time. Hence, prior to 1698 and the invention of the Savery Engine, horses were used to power pulleys, attached to buckets, which lifted water out of flooded salt mines in England. In the years to follow, more variations of steam engines were built, such as the Newcomen Engine, and later the Watt Engine. In time, these early engines would eventually be utilized in place of horses. Thus, each engine began to be associated with a certain amount of "horse power" depending upon how many horses it had replaced. The main problem with these first engines was that they were slow and clumsy, converting less than 2% of the input fuel into useful work. In other words, large quantities of coal (or wood) had to be burned to yield only a small fraction of work output. Hence the need for a new science of engine dynamics was born.

18th-century developments

During the 18th century, the mechanics founded by Newton was developed by several scientists as more mathematicians learned calculus and elaborated upon its initial formulation. The application of mathematical analysis to problems of motion was known as rational mechanics, or mixed mathematics (and was later termed classical mechanics).

Mechanics

In 1714, Brook Taylor derived the fundamental frequency of a stretched vibrating string in terms of its tension and mass per unit length by solving a differential equation. The Swiss mathematician Daniel Bernoulli (1700–1782) made important mathematical studies of the behavior of gases, anticipating the kinetic theory of gases developed more than a century later, and has been referred to as the first mathematical physicist. In 1733, Daniel Bernoulli derived the fundamental frequency and harmonics of a hanging chain by solving a differential equation. In 1734, Bernoulli solved the differential equation for the vibrations of an elastic bar clamped at one end. Bernoulli's treatment of fluid dynamics and his examination of fluid flow was introduced in his 1738 work *Hydrodynamica*.

Rational mechanics dealt primarily with the development of elaborate mathematical treatments of observed motions, using Newtonian principles as a basis, and emphasized improving the tractability of complex calculations and developing of legitimate means of analytical approximation. A representative contemporary textbook was published by Johann Baptiste Horvath. By the end of the century analytical treatments were rigorous enough to verify the stability of the solar system solely on the basis of Newton's laws without reference to divine intervention—even as deterministic treatments of systems as simple as the three body problem in gravitation remained intractable. In 1705, Edmond Halley predicted the periodicity of Halley's Comet, William Herschel discovered Uranus in

1781, and Henry Cavendish measured the gravitational constant and determined the mass of the Earth in 1798. In 1783, John Michell suggested that some objects might be so massive that not even light could escape from them.

In 1739, Leonhard Euler solved the ordinary differential equation for a forced harmonic oscillator and noticed the resonance phenomenon. In 1742, Colin Maclaurin discovered his uniformly rotating self-gravitating spheroids. In 1742, Benjamin Robins published his *New Principles in Gunnery*, establishing the science of aerodynamics. British work, carried on by mathematicians such as Taylor and Maclaurin, fell behind Continental developments as the century progressed. Meanwhile, work flourished at scientific academies on the Continent, led by such mathematicians as Bernoulli, Euler, Lagrange, Laplace, and Legendre. In 1743, Jean le Rond d'Alembert published his *Traite de Dynamique*, in which he introduced the concept of generalized forces for accelerating systems and systems with constraints, and applied the new idea of virtual work to solve dynamical problem, now known as D'Alembert's principle, as a rival to Newton's second law of motion. In 1747, Pierre Louis Maupertuis applied minimum principles to mechanics. In 1759, Euler solved the partial differential equation for the vibration of a rectangular drum. In 1764, Euler examined the partial differential equation for the vibration of a circular drum and found one of the Bessel function solutions. In 1776, John Smeaton published a paper on experiments relating power, work, momentum and kinetic energy, and supporting the conservation of energy. In 1788, Joseph Louis Lagrange presented Lagrange's equations of motion in *Mécanique Analytique*, in which the whole of mechanics was organized around the principle of virtual work.

In 1789, Antoine Lavoisier states the law of conservation of mass. The rational mechanics developed in the 18th century received a brilliant exposition in both Lagrange's 1788 work and the *Celestial Mechanics* (1799–1825) of Pierre-Simon Laplace.

Thermodynamics

During the 18th century, thermodynamics was developed through the theories of weightless "imponderable fluids", such as heat ("caloric"), electricity, and phlogiston (which was rapidly overthrown as a concept following Lavoisier's identification of oxygen gas late in the century). Assuming that these concepts were real fluids, their flow could be traced through a mechanical apparatus or chemical reactions. This tradition of experimentation led to the development of new kinds of experimental apparatus, such as the Leyden Jar; and new kinds of measuring instruments, such as the calorimeter, and improved versions of old ones, such as the thermometer. Experiments also produced new concepts, such as the University of Glasgow experimenter Joseph Black's notion of latent heat and Philadelphia intellectual Benjamin Franklin's characterization of electrical fluid as flowing between places of excess and deficit (a concept later reinterpreted in terms of positive and negative charges). Franklin also showed that lightning is electricity in 1752.

The accepted theory of heat in the 18th century viewed it as a kind of fluid, called caloric; although this theory was later shown to be erroneous, a number of scientists adhering to it nevertheless made important discoveries useful in developing the modern theory, including Joseph Black (1728–99) and

Henry Cavendish (1731–1810). Opposed to this caloric theory, which had been developed mainly by the chemists, was the less accepted theory dating from Newton's time that heat is due to the motions of the particles of a substance. This mechanical theory gained support in 1798 from the cannon-boring experiments of Count Rumford (Benjamin Thompson), who found a direct relationship between heat and mechanical energy.

While it was recognized early in the 18th century that finding absolute theories of electrostatic and magnetic force akin to Newton's principles of motion would be an important achievement, none were forthcoming. This impossibility only slowly disappeared as experimental practice became more widespread and more refined in the early years of the 19th century in places such as the newly established Royal Institution in London. Meanwhile, the analytical methods of rational mechanics began to be applied to experimental phenomena, most influentially with the French mathematician Joseph Fourier's analytical treatment of the flow of heat, as published in 1822. Joseph Priestley proposed an electrical inverse-square law in 1767, and Charles-Augustin de Coulomb introduced the inverse-square law of electrostatics in 1798.

At the end of the century, the members of the French Academy of Sciences had attained clear dominance in the field. At the same time, the experimental tradition established by Galileo and his followers persisted. The Royal Society and the French Academy of Sciences were major centers for the performance and reporting of experimental work. Experiments in mechanics, optics, magnetism, static electricity, chemistry, and physiology were not clearly distinguished from each other during the 18th century, but significant differences in explanatory schemes and, thus, experiment design were emerging. Chemical experimenters, for instance, defied attempts to enforce a scheme of abstract Newtonian forces onto chemical affiliations, and instead focused on the isolation and classification of chemical substances and reactions.

19th century

Mechanics

In 1821, William Hamilton began his analysis of Hamilton's characteristic function. In 1835, he stated Hamilton's canonical equations of motion.

In 1813, Peter Ewart supported the idea of the conservation of energy in his paper *On the measure of moving force*. In 1829, Gaspard Coriolis introduced the terms of work (force times distance) and kinetic energy with the meanings they have today. In 1841, Julius Robert von Mayer, an amateur scientist, wrote a paper on the conservation of energy, although his lack of academic training led to its rejection. In 1847, Hermann von Helmholtz formally stated the law of conservation of energy.

Electromagnetism

In 1800, Alessandro Volta invented the electric battery (known as the voltaic pile) and thus improved the way electric currents could also be studied. A year later, Thomas Young demonstrated the wave nature of light—which received strong experimental support from the work of Augustin-Jean Fresnel— and the principle of interference. In 1820, Hans Christian Ørsted found that a current-carrying conductor gives rise to a magnetic force surrounding it, and within a week after Ørsted's discovery reached France, André-Marie Ampère discovered that two parallel electric currents will exert forces on each other. In 1821, Michael Faraday built an electricity-powered motor, while Georg Ohm stated his law of electrical resistance in 1826, expressing the relationship between voltage, current, and resistance in an electric circuit.

In 1831, Faraday (and independently Joseph Henry) discovered the reverse effect, the production of an electric potential or current through magnetism – known as electromagnetic induction; these two discoveries are the basis of the electric motor and the electric generator, respectively.

Laws of thermodynamics

In the 19th century, the connection between heat and mechanical energy was established quantitatively by Julius Robert von Mayer and James Prescott Joule, who measured the mechanical equivalent of heat in the 1840s. In 1849, Joule published results from his series of experiments (including the paddlewheel experiment) which show that heat is a form of energy, a fact that was accepted in the 1850s. The relation between heat and energy was important for the development of steam engines, and in 1824 the experimental and theoretical work of Sadi Carnot was published. Carnot captured some of the ideas of thermodynamics in his discussion of the efficiency of an idealized engine. Sadi Carnot's work provided a basis for the formulation of the first law of thermodynamics—a restatement of the law of conservation of energy—which was stated around 1850 by William Thomson, later known as Lord Kelvin, and Rudolf Clausius. Lord Kelvin, who had extended the concept of absolute zero from gases to all substances in 1848, drew upon the engineering theory of Lazare Carnot, Sadi Carnot, and Émile Clapeyron–as well as the experimentation of James Prescott Joule on the interchangeability of mechanical, chemical, thermal, and electrical forms of work—to formulate the first law.

Kelvin and Clausius also stated the second law of thermodynamics, which was originally formulated in terms of the fact that heat does not spontaneously flow from a colder body to a hotter. Other formulations followed quickly (for example, the second law was expounded in Thomson and Peter Guthrie Tait's influential work *Treatise on Natural Philosophy*) and Kelvin in particular understood some of the law's general implications. The second Law was the idea that gases consist of molecules in motion had been discussed in some detail by Daniel Bernoulli in 1738, but had fallen out of favor, and was revived by Clausius in 1857. In 1850, Hippolyte Fizeau and Léon Foucault measured the speed of light in water and find that it is slower than in air, in support of the wave model of light. In 1852, Joule and Thomson demonstrated that a rapidly expanding gas cools, later named the Joule–Thomson effect or Joule–Kelvin effect. Hermann von Helmholtz puts forward the idea of the heat death of the universe in 1854, the same year that Clausius established the importance of dQ/T (Clausius's theorem) (though he did not yet name the quantity).

Statistical mechanics (a fundamentally new approach to science)

In 1859, James Clerk Maxwell discovered the distribution law of molecular velocities. Maxwell showed that electric and magnetic fields are propagated outward from their source at a speed equal to that of light and that light is one of several kinds of electromagnetic radiation, differing only in frequency and wavelength from the others. In 1859, Maxwell worked out the mathematics of the distribution of velocities of the molecules of a gas. The wave theory of light was widely accepted by the time of Maxwell's work on the electromagnetic field, and afterward the study of light and that of electricity and magnetism were closely related. In 1864 James Maxwell published his papers on a dynamical theory of the electromagnetic field, and stated that light is an electromagnetic phenomenon in the 1873 publication of Maxwell's *Treatise on Electricity and Magnetism*. This work drew upon theoretical work by German theoreticians such as Carl Friedrich Gauss and Wilhelm Weber. The encapsulation of heat in particulate motion, and the addition of electromagnetic forces to Newtonian dynamics established an enormously robust theoretical underpinning to physical observations.

The prediction that light represented a transmission of energy in wave form through a "luminiferous ether", and the seeming confirmation of that prediction with Helmholtz student Heinrich Hertz's 1888 detection of electromagnetic radiation, was a major triumph for physical theory and raised the possibility that even more fundamental theories based on the field could soon be developed. Experimental confirmation of

Maxwell's theory was provided by Hertz, who generated and detected electric waves in 1886 and verified their properties, at the same time foreshadowing their application in radio, television, and other devices. In 1887, Heinrich Hertz discovered the photoelectric effect. Research on the electromagnetic waves began soon after, with many scientists and inventors conducting experiments on their properties. In the mid to late 1890s Guglielmo Marconi developed a radio wave based wireless telegraphy system (see invention of radio).

The atomic theory of matter had been proposed again in the early 19th century by the chemist John Dalton and became one of the hypotheses of the kinetic-molecular theory of gases developed by Clausius and James Clerk Maxwell to explain the laws of thermodynamics.

The kinetic theory in turn led to a revolutionary approach to science, the statistical mechanics of Ludwig Boltzmann (1844–1906) and Josiah Willard Gibbs (1839–1903), which studies the statistics of microstates of a system and uses statistics to determine the state of a physical system. Interrelating the statistical likelihood of certain states of organization of these particles with the energy of those states, Clausius reinterpreted the dissipation of energy to be the statistical tendency of molecular configurations to pass toward increasingly likely, increasingly disorganized states (coining the term "entropy" to describe the disorganization of a state). The statistical versus absolute interpretations of the second law of thermodynamics set up a dispute that would last for several decades (producing arguments such as "Maxwell's demon"), and that would not be held to be definitively resolved until the behavior of atoms was firmly established in the early

20th century. In 1902, James Jeans found the length scale required for gravitational perturbations to grow in a static nearly homogeneous medium.

Other developments

In 1822, botanist Robert Brown discovered Brownian motion: pollen grains in water undergoing movement resulting from their bombardment by the fast-moving atoms or molecules in the liquid.

In 1834, Carl Jacobi discovered his uniformly rotating self-gravitating ellipsoids (the Jacobi ellipsoid).

In 1834, John Russell observed a nondecaying solitary water wave (soliton) in the Union Canal near Edinburgh and used a water tank to study the dependence of solitary water wave velocities on wave amplitude and water depth. In 1835, Gaspard Coriolis examined theoretically the mechanical efficiency of waterwheels, and deduced the Coriolis effect. In 1842, Christian Doppler proposed the Doppler effect.

In 1851, Léon Foucault showed the Earth's rotation with a huge pendulum (Foucault pendulum).

There were important advances in continuum mechanics in the first half of the century, namely formulation of laws of elasticity for solids and discovery of Navier–Stokes equations for fluids.

20th century: birth of modern physics

At the end of the 19th century, physics had evolved to the point at which classical mechanics could cope with highly complex problems involving macroscopic situations; thermodynamics and kinetic theory were well established; geometrical and physical optics could be understood in terms of electromagnetic waves; and the conservation laws for energy and momentum (and mass) were widely accepted. So profound were these and other developments that it was generally accepted that all the important laws of physics had been discovered and that, henceforth, research would be concerned with clearing up minor problems and particularly with improvements of method and measurement. However, around 1900 serious doubts arose about the completeness of the classical theories—the triumph of Maxwell's theories, for example, was undermined by inadequacies that had already begun to appear—and their inability to explain certain physical phenomena, such as the energy distribution in blackbody radiation and the photoelectric effect, while some of the theoretical formulations led to paradoxes when pushed to the limit. Prominent physicists such as Hendrik Lorentz, Emil Cohn, Ernst Wiechert and Wilhelm Wien believed that some modification of Maxwell's equations might provide the basis for all physical laws. These shortcomings of classical physics were never to be resolved and new ideas were required. At the beginning of the 20th century a major revolution shook the world of physics, which led to a new era, generally referred to as modern physics.

Radiation experiments

In the 19th century, experimenters began to detect unexpected forms of radiation: Wilhelm Röntgen caused a sensation with his discovery of X-rays in 1895; in 1896 Henri Becquerel discovered that certain kinds of matter emit radiation on their own accord. In 1897, J. J. Thomson discovered the electron, and new radioactive elements found by Marie and Pierre Curie raised questions about the supposedly indestructible atom and the nature of matter. Marie and Pierre coined the term "radioactivity" to describe this property of matter, and isolated the radioactive elements radium and polonium. Ernest Rutherford and Frederick Soddy identified two of Becquerel's forms of radiation with electrons and the element helium. Rutherford identified and named two types of radioactivity and in 1911 interpreted experimental evidence as showing that the atom consists of a dense, positively charged nucleus surrounded by negatively charged electrons. Classical theory, however, predicted that this structure should be unstable. Classical theory had also failed to explain successfully two other experimental results that appeared in the late 19th century. One of these was the demonstration by Albert A. Michelson and Edward W. Morley—known as the Michelson–Morley experiment—which showed there did not seem to be a preferred frame of reference, at rest with respect to the hypothetical luminiferous ether, for describing electromagnetic phenomena. Studies of radiation and radioactive decay continued to be a preeminent focus for physical and chemical research through the 1930s, when the discovery of nuclear fission by Lise Meitner and Otto Frisch opened the way to the practical exploitation of what came to be called "atomic" energy.

Albert Einstein's theory of relativity

In 1905, a 26-year-old German physicist named Albert Einstein (then a patent clerk in Bern, Switzerland) showed how measurements of time and space are affected by motion between an observer and what is being observed. Einstein's radical theory of relativity revolutionized science. Although Einstein made many other important contributions to science, the theory of relativity alone represents one of the greatest intellectual achievements of all time. Although the concept of relativity was not introduced by Einstein, his major contribution was the recognition that the speed of light in a vacuum is constant, i.e. the same for all observers, and an absolute physical boundary for motion. This does not impact a person's day-to-day life since most objects travel at speeds much slower than light speed. For objects travelling near light speed, however, the theory of relativity shows that clocks associated with those objects will run more slowly and that the objects shorten in length according to measurements of an observer on Earth. Einstein also derived the famous equation, $E = mc$, which expresses the equivalence of mass and energy.

Special relativity

Einstein argued that the speed of light was a constant in all inertial reference frames and that electromagnetic laws should remain valid independent of reference frame—assertions which rendered the ether "superfluous" to physical theory, and that held that observations of time and length varied relative to how the observer was moving with respect to the object being measured (what came to be called the "special theory of relativity"). It also followed that mass and energy were interchangeable quantities according to the equation *E=mc*. In another paper published the same year, Einstein asserted that electromagnetic radiation was transmitted in discrete quantities ("quanta"), according to a constant that the theoretical physicist Max Planck had posited in 1900 to arrive at an accurate theory for the distribution of blackbody radiation—an assumption that explained the strange properties of the photoelectric effect.

The special theory of relativity is a formulation of the relationship between physical observations and the concepts of space and time. The theory arose out of contradictions between electromagnetism and Newtonian mechanics and had great impact on both those areas. The original historical issue was whether it was meaningful to discuss the electromagnetic wave-carrying "ether" and motion relative to it and also whether one could detect such motion, as was unsuccessfully attempted in the Michelson–Morley experiment. Einstein demolished these questions and the ether concept in his special theory of relativity. However, his basic formulation does not involve detailed electromagnetic theory. It arises out of the question: "What is time?" Newton, in the *Principia* (1686), had given an unambiguous answer: "Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration." This definition is basic to all classical physics.

Einstein had the genius to question it, and found that it was incomplete. Instead, each "observer" necessarily makes use of his or her own scale of time, and for two observers in relative motion, their time-scales will differ. This induces a related effect on position measurements. Space and time become intertwined concepts, fundamentally dependent on the observer. Each observer presides over his or her own space-time framework or coordinate system. There being no absolute frame of reference, all observers of given events make different but equally valid (and reconcilable) measurements. What remains absolute is stated in Einstein's relativity postulate: "The basic laws of physics are identical for two observers who have a constant relative velocity with respect to each other."

Special relativity had a profound effect on physics: started as a rethinking of the theory of electromagnetism, it found a new symmetry law of nature, now called *Poincaré symmetry*, that replaced the old Galilean symmetry.

Special relativity exerted another long-lasting effect on dynamics. Although initially it was credited with the "unification of mass and energy", it became evident that relativistic dynamics established a firm *distinction* between rest mass, which is an invariant (observer independent) property of a particle or system of particles, and the energy and momentum of a system. The latter two are separately conserved in all situations but not invariant with respect to different observers. The term *mass* in particle physics underwent a semantic change, and since the late 20th century it almost exclusively denotes the rest (or *invariant*) mass.

General relativity

By 1916, Einstein was able to generalize this further, to deal with all states of motion including non-uniform acceleration, which became the general theory of relativity. In this theory Einstein also specified a new concept, the curvature of space-time, which described the gravitational effect at every point in space. In fact, the curvature of space-time completely replaced Newton's universal law of gravitation. According to Einstein, gravitational force in the normal sense is a kind of illusion caused by the geometry of space. The presence of a mass causes a curvature of space-time in the vicinity of the mass, and this curvature dictates the space-time path that all freely-moving objects must follow. It was also predicted from this theory that light should be subject to gravity - all of which was verified experimentally. This aspect of relativity explained the phenomena of light bending around the sun, predicted black holes as well as properties of the Cosmic microwave background radiation — a discovery rendering fundamental anomalies in the classic Steady-State hypothesis. For his work on relativity, the photoelectric effect and blackbody radiation, Einstein received the Nobel Prize in 1921.

The gradual acceptance of Einstein's theories of relativity and the quantized nature of light transmission, and of Niels Bohr's model of the atom created as many problems as they solved, leading to a full-scale effort to reestablish physics on new fundamental principles. Expanding relativity to cases of accelerating reference frames (the "general theory of relativity") in the 1910s, Einstein posited an equivalence between the inertial force of acceleration and the force of gravity, leading to the conclusion that space is curved and finite in size, and the prediction of such phenomena as gravitational lensing and the distortion of time in gravitational fields.

Quantum mechanics

- Although relativity resolved the electromagnetic phenomena conflict demonstrated by Michelson and Morley, a second theoretical problem was the explanation of the distribution of electromagnetic radiation emitted by a black body; experiment showed that at shorter wavelengths, toward the ultraviolet end of the spectrum, the energy approached zero, but classical theory predicted it should become infinite. This glaring discrepancy, known as the ultraviolet catastrophe, was solved by the new theory of quantum mechanics. Quantum mechanics is the theory of atoms and subatomic systems. Approximately the first 30 years of the 20th century represent the time of the conception and evolution of the theory. The basic ideas of quantum theory were introduced in 1900 by Max Planck (1858–1947), who was awarded the Nobel Prize for Physics in 1918 for his discovery of the quantified nature of energy. The quantum theory (which previously relied in the "correspondence" at large scales between the quantized world of the atom and the continuities of the "classical" world) was accepted when the Compton Effect established that light carries momentum and can scatter off particles, and when Louis de Broglie asserted that matter can be seen as behaving as a wave in much the same way as electromagnetic waves behave like particles (wave–particle duality).

In 1905, Einstein used the quantum theory to explain the photoelectric effect, and in 1913 the Danish physicist Niels Bohr used the same constant to explain the stability of Rutherford's atom as well as the frequencies of light emitted by hydrogen gas. The quantized theory of the atom gave way to a full-scale quantum mechanics in the 1920s. New principles of a "quantum" rather than a "classical" mechanics, formulated in matrix-form by Werner Heisenberg, Max Born, and Pascual Jordan in 1925, were based on the probabilistic relationship between discrete "states" and denied the possibility of causality. Quantum mechanics was extensively developed by Heisenberg, Wolfgang Pauli, Paul Dirac, and Erwin Schrödinger, who established an equivalent theory based on waves in 1926; but Heisenberg's 1927 "uncertainty principle" (indicating the impossibility of precisely and simultaneously measuring position and momentum) and the "Copenhagen interpretation" of quantum mechanics (named after Bohr's home city) continued to deny the possibility of fundamental causality, though opponents such as Einstein would metaphorically assert that "God does not play dice with the universe". The new quantum mechanics became an indispensable tool in the investigation and explanation of phenomena at the atomic level. Also in the 1920s, the Indian scientist Satyendra Nath Bose's work on photons and quantum mechanics provided the foundation for Bose–Einstein statistics, the theory of the Bose–Einstein condensate.

The spin–statistics theorem established that any particle in quantum mechanics may be either a boson (statistically Bose–

Einstein) or a fermion (statistically Fermi–Dirac). It was later found that all fundamental bosons transmit forces, such as the photon that transmits electromagnetism.

Fermions are particles "like electrons and nucleons" and are the usual constituents of matter. Fermi–Dirac statistics later found numerous other uses, from astrophysics (see Degenerate matter) to semiconductor design.

Contemporary and particle physics

Quantum field theory

As the philosophically inclined continued to debate the fundamental nature of the universe, quantum theories continued to be produced, beginning with Paul Dirac's formulation of a relativistic quantum theory in 1928. However, attempts to quantize electromagnetic theory entirely were stymied throughout the 1930s by theoretical formulations yielding infinite energies. This situation was not considered adequately resolved until after World War II ended, when Julian Schwinger, Richard Feynman and Sin-Itiro Tomonaga independently posited the technique of renormalization, which allowed for an establishment of a robust quantum electrodynamics (QED).

Meanwhile, new theories of fundamental particles proliferated with the rise of the idea of the quantization of fields through "exchange forces" regulated by an exchange of short-lived "virtual" particles, which were allowed to exist according to the laws governing the uncertainties inherent in the quantum world. Notably, Hideki Yukawa proposed that the positive charges of the nucleus were kept together courtesy of a powerful but short-range force mediated by a particle with a mass between that of the electron and proton. This particle, the "pion", was identified in 1947 as part of what became a slew of particles discovered after World War II. Initially, such particles were found as ionizing radiation left by cosmic rays, but increasingly came to be produced in newer and more powerful particle accelerators.

Outside particle physics, significant advances of the time were:

- the invention of the laser (1964 Nobel Prize in Physics);
- the theoretical and experimental research of superconductivity, especially the invention of a quantum theory of superconductivity by Vitaly Ginzburg and Lev Landau (1962 Nobel Prize in Physics) and, later, its explanation via Cooper pairs (1972 Nobel Prize in Physics). The Cooper pair was an early example of quasiparticles.

Unified field theories

- Einstein deemed that all fundamental interactions in nature can be explained in a single theory. Unified field theories were numerous attempts to "merge" several interactions. One of formulations of such theories (as well as field theories in general) is a *gauge theory*, a generalization of the idea of symmetry. Eventually the Standard Model (see below) succeeded in unification of strong, weak, and electromagnetic interactions. All attempts to unify gravitation with something else failed.

Standard Model

When parity was broken in weak interactions by Chien-Shiung Wu in her experiment, a series of discoveries were created thereafter. The interaction of these particles by scattering and decay provided a key to new fundamental quantum theories. Murray Gell-Mann and Yuval Ne'eman brought some order to these new particles by classifying them according to certain qualities, beginning with what Gell-Mann referred to as the "Eightfold Way". While its further development, the quark model, at first seemed inadequate to describe strong nuclear forces, allowing the temporary rise of competing theories such as the S-Matrix, the establishment of quantum chromodynamics in the 1970s finalized a set of fundamental and exchange particles, which allowed for the establishment of a "standard model" based on the mathematics of gauge invariance, which successfully described all forces except for gravitation, and which remains generally accepted within its domain of application.

The Standard Model, based on the Yang-Mills Theory groups the electroweak interaction theory and quantum chromodynamics into a structure denoted by the gauge group SU(3)×SU(2)×U(1). The formulation of the unification of the electromagnetic and weak interactions in the standard model is due to Abdus Salam, Steven Weinberg and, subsequently, Sheldon Glashow. Electroweak theory was later confirmed experimentally (by observation of neutral weak currents), and distinguished by the 1979 Nobel Prize in Physics.

Since the 1970s, fundamental particle physics has provided insights into early universe cosmology, particularly the Big Bang theory proposed as a consequence of Einstein's general theory of relativity. However, starting in the 1990s, astronomical observations have also provided new challenges, such as the need for new explanations of galactic stability ("dark matter") and the apparent acceleration in the expansion of the universe ("dark energy").

While accelerators have confirmed most aspects of the Standard Model by detecting expected particle interactions at various collision energies, no theory reconciling general relativity with the Standard Model has yet been found, although supersymmetry and string theory were believed by many theorists to be a promising avenue forward. The Large Hadron Collider, however, which began operating in 2008, has failed to find any evidence whatsoever that is supportive of supersymmetry and string theory.

Cosmology

Cosmology may be said to have become a serious research question with the publication of Einstein's General Theory of Relativity in 1915 although it did not enter the scientific mainstream until the period known as the "Golden age of general relativity".

About a decade later, in the midst of what was dubbed the "Great Debate", Hubble and Slipher discovered the expansion of universe in the 1920s measuring the redshifts of Doppler spectra from galactic nebulae. Using Einstein's general relativity, Lemaître and Gamow formulated what would become known as the big bang theory. A rival, called the steady state theory was devised by Hoyle, Gold, Narlikar and Bondi.

Cosmic background radiation was verified in the 1960s by Penzias and Wilson, and this discovery favoured the big bang at the expense of the steady state scenario. Later work was by Smoot et al. (1989), among other contributors, using data from the Cosmic Background explorer (CoBE) and the Wilkinson Microwave Anisotropy Probe (WMAP) satellites that refined these observations. The 1980s (the same decade of the COBE measurements) also saw the proposal of inflation theory by Guth.

Recently the problems of dark matter and dark energy have risen to the top of the cosmology agenda.

Higgs boson

On July 4, 2012, physicists working at CERN's Large Hadron Collider announced that they had discovered a new subatomic particle greatly resembling the Higgs boson, a potential key to an understanding of why elementary particles have mass and indeed to the existence of diversity and life in the universe. For now, some physicists are calling it a "Higgslike" particle. Joe Incandela, of the University of California, Santa Barbara, said, "It's something that may, in the end, be one of the biggest observations of any new phenomena in our field in the last 30 or 40 years, going way back to the discovery of quarks, for example." Michael Turner, a cosmologist at the University of Chicago and the chairman of the physics center board, said:

"*This is a big moment for particle physics and a crossroads — will this be the high water mark or will it be the first of many discoveries that point us toward solving the really big questions that we have posed?*"

- *—Michael Turner, University of Chicago*

Peter Higgs was one of six physicists, working in three independent groups, who, in 1964, invented the notion of the Higgs field ("cosmic molasses"). The others were Tom Kibble of Imperial College, London; Carl Hagen of the University of Rochester; Gerald Guralnik of Brown University; and François Englert and Robert Brout, both of Université libre de Bruxelles.

Although they have never been seen, Higgslike fields play an important role in theories of the universe and in string theory. Under certain conditions, according to the strange accounting of Einsteinian physics, they can become suffused with energy that exerts an antigravitational force. Such fields have been proposed as the source of an enormous burst of expansion, known as inflation, early in the universe and, possibly, as the secret of the dark energy that now seems to be speeding up the expansion of the universe.

Physical sciences

With increased accessibility to and elaboration upon advanced analytical techniques in the 19th century, physics was defined as much, if not more, by those techniques than by the search for universal principles of motion and energy, and the fundamental nature of matter. Fields such as acoustics, geophysics, astrophysics, aerodynamics, plasma physics, low-temperature physics, and solid-state physics joined optics, fluid dynamics, electromagnetism, and mechanics as areas of physical research. In the 20th century, physics also became closely allied with such fields as electrical, aerospace and materials engineering, and physicists began to work in government and industrial laboratories as much as in academic settings. Following World War II, the population of physicists increased dramatically, and came to be centered on the United States, while, in more recent decades, physics has become a more international pursuit than at any time in its previous history.

Chapter 27

Science in Classical Antiquity

Science in classical antiquity encompasses inquiries into the workings of the world or universe aimed at both practical goals (e.g., establishing a reliable calendar or determining how to cure a variety of illnesses) as well as more abstract investigations belonging to natural philosophy. The ancient peoples who are considered today as the first scientists may have thought of themselves as natural philosophers, as practitioners of a skilled profession (for example, physicians), or as followers of a religious tradition (for example, temple healers). Some of these figures include Hippocrates, Aristotle, Euclid, Archimedes, Hipparchus, Galen, and Ptolemy. Their works and commentaries spread throughout the Eastern, Islamic, and Latin worlds and became the wellspring of science.

Classical Greece

Practical knowledge

The practical concerns of the ancient Greeks to establish a calendar is first exemplified by the *Works and Days* of the Greek poet Hesiod, who lived around 700 BC. The *Works and Days* incorporated a calendar, in which the farmer was to regulate seasonal activities by the seasonal appearances and disappearances of the stars, as well as by the phases of the Moon which were held to be propitious or ominous. Around 450

BC we begin to see compilations of the seasonal appearances and disappearances of the stars in texts known as *parapegmata*, which were used to regulate the civil calendars of the Greek city-states on the basis of astronomical observations.

Medicine provides another example of practically oriented investigation of nature among the Ancient Greeks. It has been pointed out that Greek medicine was not the province of a single trained profession and there was no accepted method of qualification of licensing. Physicians in the Hippocratic tradition, temple healers associated with the cult of Asclepius, herb collectors, drug sellers, midwives, and gymnastic trainers all claimed to be qualified as healers in specific contexts and competed actively for patients. This rivalry among these competing traditions contributed to an active public debate about the causes and proper treatment of disease, and about the general methodological approaches of their rivals. In the Hippocratic text, *On the Sacred Disease*, which deals with the nature of epilepsy, the author attacks his rivals (temple healers) for their ignorance and for their love of gain. The author of this text seems modern and progressive when he insists that epilepsy has a natural cause, yet when he comes to explain what that cause is and what the proper treatment would be, his explanation is as short on specific evidence and his treatment as vague as that of his rivals.

There were several acute observers of natural phenomena, especially Aristotle and Theophrastus, who wrote extensively on animals and plants. Theophrastus also produced the first systematic attempt to classify minerals and rocks, summarised in the *Natural History* of Pliny the Elder in 77 AD. The important legacy of this period of Greek science included substantial advances in factual knowledge, especially in anatomy, zoology, botany, mineralogy and astronomy; an awareness of the importance of certain scientific problems, especially those related to the problem of change and its causes; and a recognition of the methodological importance of applying mathematics to natural phenomena and of undertaking empirical research.

Pre-Socratic philosophers

Materialist philosophers

The earliest Greek philosophers, known as the pre-Socratics, were materialists who provided alternative answers to the same question found in the myths of their neighbors: "How did the ordered cosmos in which we live come to be?" But although the question is much the same, their answers and their attitude towards the answers is markedly different. As reported by such later writers as Aristotle, their explanations tended to center on the material source of things.

Thales of Miletus (624–546 BC) considered that all things came to be from and find their sustenance in water. Anaximander (610–546 BC) then suggested that things could not come from a specific substance like water, but rather from something he called the "boundless." Exactly what he meant is uncertain but it has been suggested that it was boundless in its quantity, so that creation would not fail; in its qualities, so that it would not be overpowered by its contrary; in time, as it has no beginning or end; and in space, as it encompasses all things.

Anaximenes (585–525 BC) returned to a concrete material substance, air, which could be altered by rarefaction and condensation. He adduced common observations (the wine stealer) to demonstrate that air was a substance and a simple experiment (breathing on one's hand) to show that it could be altered by rarefaction and condensation.

Heraclitus of Ephesus (about 535–475 BC), then maintained that change, rather than any substance was fundamental, although the element fire seemed to play a central role in this process. Finally, Empedocles of Acragas (490–430 BC), seems to have combined the views of his predecessors, asserting that there are four elements (Earth, Water, Air and Fire) which produce change by mixing and separating under the influence of two opposing "forces" that he called Love and Strife.

All these theories imply that matter is a continuous substance. Two Greek philosophers, Leucippus (first half of the 5th century BC) and Democritus came up with the notion that there were two real entities: atoms, which were small indivisible particles of matter, and the void, which was the empty space in which matter was located. Although all the explanations from Thales to Democritus involve matter, what is more important is the fact that these rival explanations suggest an ongoing process of debate in which alternate theories were put forth and criticized.

Xenophanes of Colophon prefigured paleontology and geology as he thought that periodically the earth and sea mix and turn all to mud, citing several fossils of sea creatures that he had seen.

Pythagorean philosophy

The materialist explanations of the origins of the cosmos were attempts at answering the question of how an organized universe came to be; however, the idea of a random assemblage of elements (e.g., fire or water) producing an ordered universe without the existence of some ordering principle remained problematic to some.

An answer to this conundrum was that of the followers of Pythagoras (c. 582–507 BC), who saw number as the fundamental unchanging entity underlying all the structure of the universe. Although it is difficult to separate fact from legend, it appears that some Pythagoreans believed matter to be made up of ordered arrangements of points according to geometrical principles: triangles, squares, rectangles, or other figures. Likewise, the universe was arranged on the basis of numbers, ratios, and proportions much like musical scales. Philolaus, for instance, held that there were ten heavenly bodies because the sum of 1 + 2 + 3 + 4 gives the perfect number 10. Thus, the Pythagoreans were some of the first to apply mathematical principles to explain the rational basis of an orderly universe— an idea that was to have immense consequences in the development of scientific thought.

Plato and Aristotle

Plato (c. 427–c. 347 BC), perhaps under Pythagorean influence, also identified the ordering principle of the universe as one based on number and geometry. A later account has it that Plato had inscribed at the entrance to the Academy the words

"Let no man ignorant of geometry enter." Although the story is most likely a myth, it nonetheless testifies to Plato's interest in mathematics, which is alluded to in several of his dialogues.

In his philosophy Plato maintained that all material things are imperfect reflections of eternal unchanging ideas, just as all mathematical diagrams are reflections of eternal unchanging mathematical truths. Since Plato believed that material things had an inferior kind of reality, he considered that demonstrative knowledge cannot be achieved by looking at the imperfect material world. Truth is to be found through rational argumentation, analogous to the demonstrations of mathematicians. For instance, Plato recommended that astronomy be studied in terms of abstract geometrical models rather than empirical observations, and proposed that leaders be trained in mathematics in preparation for philosophy.

Aristotle (384–322 BC), who studied at the Academy, nonetheless disagreed with Plato in several important respects. While he agreed that truth must be eternal and unchanging, he maintained that the world is knowable through experience and that we come to know the truth by what we perceive with our senses. For Aristotle, directly observable things are real; ideas (or as he called them, forms) only exist as they express themselves in matter, such as in living things, or in the mind of an observer or artisan.

Aristotle's theory of reality led to a different approach to science:

- First, Aristotle emphasized observation of the material entities which embody the forms.

- Second, he played down (but did not negate) the importance of mathematics.
- Third, he emphasized the process of change where Plato had emphasized eternal unchanging ideas.
- Fourth, he reduced the importance of Plato's ideas to one of four causal factors.

Aristotle thus distinguished between four causes:

- the matter of which a thing was made (the material cause).
- the form into which it was made (the formal cause; similar to Plato's ideas).
- the agent who made the thing (the moving or efficient cause).
- the purpose for which the thing was made (the final cause).

Aristotle insisted that scientific knowledge (Ancient Greek: ἐπιστήμη, Latin: *scientia*) is knowledge of necessary causes. He and his followers would not accept mere description or prediction as science. In view of this disagreement with Plato, Aristotle established his own school, the Lyceum, which further developed and transmitted his approach to the investigation of nature.

Most characteristic of Aristotle's causes is his final cause, the purpose for which a thing is made. He came to this insight through his biological researches, such as those of marine animals at Lesbos, in which he noted that the organs of animals serve a particular function:

- The absence of chance and the serving of ends are found in the works of nature especially. And the end for the sake of which a thing has been constructed or has come to be belongs to what is beautiful.

Aristotle was one of the most prolific natural philosophers of Antiquity, and developed a comprehensive theory of physics that was a variation of the classical theory of the elements (earth, water, fire, air, and aether). In his theory, the light elements (fire and air) have a natural tendency to move away from the center of the universe while the heavy elements (earth and water) have a natural tendency to move toward the center of the universe, thereby forming a spherical earth. Since the celestial bodies (i.e., the planets and stars) were seen to move in circles, he concluded that they must be made of a fifth element, which he called aether.

Aristotle used intuitive ideas to justify his reasoning and could point to the falling stone, rising flames, or pouring water to illustrate his theory. His laws of motion emphasized the common observation that friction was an omnipresent phenomenon: that any body in motion would, unless acted upon, *come to rest*. He also proposed that heavier objects fall faster, and that voids were impossible.

Theophrastus and the Peripatetics

Aristotle's successor at the Lyceum was Theophrastus, who wrote valuable books describing plant and animal life. His works are regarded as the first to put botany and zoology on a systematic footing.

One of Theophrastus' achievements is his work on mineralogy, with descriptions of ores and minerals known to the world at that time. He made some shrewd observations of their properties. For example, he made the first known reference to the phenomenon, now known to be caused by pyroelectricity, that the mineral tourmaline attracts straws and bits of wood when heated. Pliny the Elder makes clear references to his use of the work in his *Natural History* of 77 AD, while updating and making much new information available on minerals himself. From both these early texts was to emerge the science of mineralogy, and ultimately geology. Both authors describe the sources of the minerals they discuss in the various mines exploited in their time, so their works should be regarded not just as early scientific texts, but also important for the history of engineering and the history of technology.

Other notable peripatetics include Strato, who was a tutor in the court of the Ptolemies and who devoted time to physical research, Eudemus, who edited Aristotle's works and wrote the first books on the history of science, and Demetrius of Phalerum, who governed Athens for a time and later helped establish the Library of Alexandria.

Hellenistic period

The military campaigns of Alexander the Great spread Greek thought to Egypt, Asia Minor, Persia, up to the Indus River. The resulting Hellenistic civilization produced many seats of learning, such as those in Alexandria, Antioch, and Pergamum, along with the migration of many Greek speaking populations across several territories. Hellenistic science differed from

Greek science in at least two respects: first, it benefited from the cross-fertilization of Greek ideas with those that had developed in other non-Hellenic civilizations; secondly, to some extent, it was supported by royal patrons in the kingdoms founded by Alexander's successors. The city of Alexandria, in particular, became a major center of scientific research in the 3rd century BC. Two institutions established there during the reigns of Ptolemy I Soter (reigned 323–283 BC) and Ptolemy II Philadelphus (reigned 281–246 BC) were the Library and the Museum. Unlike Plato's Academy and Aristotle's Lyceum, these institutions were officially supported by the Ptolemies; although the extent of patronage could be precarious, depending on the policies of the current ruler.

Hellenistic scholars frequently employed the principles developed in earlier Greek thought, including the application of mathematics and deliberate empirical research, in their scientific investigations.

The interpretation of Hellenistic science varies widely. At one extreme is the view of English classical scholar Cornford, who believed that "all the most important and original work was done in the three centuries from 600 to 300 BC". At the other end is the view of Italian physicist and mathematician Lucio Russo, who claims that the scientific method was actually born in the 3rd century BCE, only to be largely forgotten during the Roman period and not revived again until the Renaissance.

Technology

The level of Hellenistic achievement in astronomy and engineering is impressively shown by the Antikythera mechanism (150–100 BCE). It is a 37-gear mechanical computer which computed the motions of the Sun and Moon, including lunar and solar eclipses predicted on the basis of astronomical periods believed to have been learned from the Babylonians. Devices of this sort that use differential gearing are not known to have been engineered again until the 10th century, when a simpler eight-geared luni-solar calculator incorporated into an astrolabe was described by Persian scholar Al-Biruni. Similarly complex devices were also developed by other Muslim engineers and astronomers during the Middle Ages.

Medicine

In medicine, Herophilos (335–280 BCE) was the first to base his conclusions on dissection of the human body and to describe the nervous system. For this, he is often called as "the father of anatomy"

Mathematics

Beginning with the Hellenistic period, Greek mathematics and astronomy reached a level of sophistication not matched for several centuries afterward. Much of the work represented by scholars active in this period was of a very advanced level. There is also evidence of combining mathematical knowledge with high levels of technical expertise, as found for instance in the construction of massive building projects (e.g., the Syracusia), or in Eratosthenes' (276 – 195 BCE) measurement of the distance between the Sun and the Earth and the size of the Earth.

Although few in number, Hellenistic mathematicians actively communicated with each other; publication consisted of passing and copying someone's work among colleagues. Among their accomplishments is the work of Euclid (325 – 265 BCE), which includes the *Elements*, a canon of geometry and elementary number theory for many centuries. Archimedes (287 – 212 BCE) found many remarkable results, such as the sum of an infinite geometric series in *Quadrature of the Parabola*, an approximation to the value π in *Measurement of the Circle*, and a nomenclature to express very large numbers in the *Sand Reckoner*.

The most characteristic product of Greek mathematics may be the theory of conic sections, which was largely developed in the Hellenistic period, primarily by Apollonius (262 – 190 BCE). The methods used made no explicit use of algebra, nor trigonometry, the latter appearing around the time of Hipparchus (190 – 120 BCE).

Astronomy

Aristarchus of Samos (310 – 230 BCE) was an ancient Greek astronomer and mathematician who presented the first known heliocentric model that placed the Sun at the center of the known universe, with the Earth revolving around the Sun once a year and rotating about its axis once a day. Aristarchus also estimated the sizes of the Sun and Moon as compared to Earth's size, and the distances to the Sun and Moon. His heliocentric model did not find many adherents in antiquity but did influence some early modern astronomers, such as Nicolaus Copernicus, who was aware of the heliocentric theory of Aristarchus.

In the 2nd century BC, Hipparchus discovered precession, calculated the size and distance of the Moon and invented the earliest known astronomical devices such as the astrolabe. Hipparchus also created a comprehensive catalog of 1020 stars, and most of the constellations of the northern hemisphere derive from Greek astronomy. It has recently been claimed that a celestial globe based on Hipparchus's star catalog sits atop the broad shoulders of a large 2nd-century Roman statue known as the Farnese Atlas.

Roman era

Science during the Roman Empire period was concerned with systematizing knowledge gained in the preceding Hellenistic period and the knowledge from the vast areas the Romans had conquered. It was largely their work that would be passed on to later civilizations.

Even though science continued under Roman rule, Latin texts were mainly compilations drawing on earlier Greek work. Advanced scientific research and teaching continued to be carried on in Greek. Such Greek and Hellenistic works as survived were preserved and developed later in the Byzantine Empire and then in the Islamic world. Late Roman attempts to translate Greek writings into Latin had limited success (e.g., Boethius), and direct knowledge of most ancient Greek texts only reached western Europe from the 12th century onwards.

Pliny

Of particular importance is the *Naturalis Historia* of Pliny the Elder published in 77 CE, one of the most extensive compilations of the natural world which survived the Dark Ages. Pliny does not simply list materials and objects but also seeks explanations of phenomena. Thus he is the first to correctly describe the origin of amber as being the fossilized resin of pine trees. He makes the inference from the observation of trapped insects within some amber samples. The *Naturalis Historia* divides neatly into the organic world of plants and animals, and the realm of inorganic matter, although there are frequent digressions in each section. He is especially interested in not just describing the occurrence of plants, animals and insects, but also their exploitation (or abuse) by man. The description of metals and minerals is particularly detailed, and valuable as being the most extensive compilation still available from the ancient world. Although much of the work was compiled by judicious use of written sources, Pliny gives an eyewitness account of gold mining in Spain, where he was stationed as an officer. Pliny is especially significant because he provides full bibliographic details of the earlier authors and their works he uses and consults. Because his encyclopaedia survived the Dark Ages, we know of these lost works, even if the texts themselves have disappeared. The book was one of the first to be printed in 1489, and became a standard reference work for Renaissance scholars, as well as an inspiration for the development of a scientific and rational approach to the world.

Ptolemy

Claudius Ptolemy (c. 100-170 CE), living in or around Alexandria, carried out a massive program centering on the writing of about a dozen books on astronomy, astrology, optics, harmonics, and cartography. Despite their severe style and high technicality, a great deal of them have survived, in some cases the sole remnants of their kind of scientific writing from antiquity. Though ranging widely in subject matter, two major themes run through Ptolemy's works: mathematical modelling of physical phenomena, and methods of visual representation of physical reality.

Characteristically of Ptolemy's research program is his combination of theoretical analysis with empirical considerations. A prime example of this approach is his systematized study of astronomy. Ptolemy's *Mathēmatikē Syntaxis* (Ancient Greek: ΜαθηματικὴΣύνταξις), better known as the *Almagest*, sought to improve on the work of his predecessors by building astronomy not only upon a secure mathematical basis but also by demonstrating the relationship between astronomical observations and the resulting astronomical theory. In his *Planetary Hypotheses*, Ptolemy describes in detail physical representations of his mathematical models found in the *Almagest*, presumably for didactic purposes. Likewise, the *Geography* was concerned with the drawing of accurate maps using astronomical information, at least in principle. Apart from astronomy, both the *Harmonics* and the *Optics* contain (in addition to mathematical analyses of sound and sight, respectively) instructions on how to construct and use experimental instruments to corroborate theory.

Ptolemy's thoroughness and his preoccupation with ease of presentation (for instance, in his widespread use of tables) virtually guaranteed that earlier work on these subjects be neglected or considered obsolete, to the extent that almost nothing remains of the works Ptolemy often refers. His astronomical work in particular defined the method and subject matter of future research for centuries, and the Ptolemaic system became the dominant model for the motions of the heavens until the seventeenth century.

Galen

Around the same time, the Roman-era physician Galen (c. 129-210 CE) codified and somewhat built upon Hellenistic knowledge of anatomy and physiology. His careful dissections and observations of dogs, pigs, and Barbary apes, his descriptions (based on these and the works of earlier authors) of such structures as the nervous system, heart, and kidneys, and his demonstrations that, for instance, arteries carry blood instead of air became a central part of medical knowledge for well over a thousand years.

Hero

Hero of Alexandria was a Greco-Egyptian mathematician and engineer who is often considered to be the greatest experimenter of antiquity. Among his most famous inventions was a windwheel, constituting the earliest instance of wind harnessing on land, and a well-recognized description of a steam-powered device called an aeolipile, which was the first-recorded steam engine.

Chapter 28

Romanticism in Science

19th-century science was greatly influenced by Romanticism (or the Age of Reflection, c. 1800–40), an intellectual movement that originated in Western Europe as a counter-movement to the late-18th-century Enlightenment. Romanticism incorporated many fields of study, including politics, the arts, and the humanities.

In contrast to the Enlightenment's mechanistic natural philosophy, European scientists of the Romantic period held that observing nature implied understanding the self and that knowledge of nature "should not be obtained by force". They felt that the Enlightenment had encouraged the abuse of the sciences, and they sought to advance a new way to increase scientific knowledge, one that they felt would be more beneficial not only to mankind but to nature as well.

Romanticism advanced a number of themes: it promoted anti-reductionism (that the whole is more valuable than the parts alone) and epistemological optimism (man was connected to nature), and encouraged creativity, experience, and genius. It also emphasized the scientist's role in scientific discovery, holding that acquiring knowledge of nature meant understanding man as well; therefore, these scientists placed a high importance on respect for nature.

Romanticism declined beginning around 1840 as a new movement, positivism, took hold of intellectuals, and lasted until about 1880. As with the intellectuals who earlier had become disenchanted with the Enlightenment and had sought a new approach to science, people now lost interest in Romanticism and sought to study science using a stricter process.

Romantic science vs. Enlightenment science

As the Enlightenment had a firm hold in France during the last decades of the 18th century, the Romantic view on science was a movement that flourished in Great Britain and especially Germany in the first half of the 19th century. Both sought to increase individual and cultural self-understanding by recognizing the limits in human knowledge through the study of nature and the intellectual capacities of man. The Romantic movement, however, resulted as an increasing dislike by many intellectuals for the tenets promoted by the Enlightenment; it was felt by some that Enlightened thinkers' emphasis on rational thought through deductive reasoning and the mathematization of natural philosophy had created an approach to science that was too cold and that attempted to control nature, rather than to peacefully co-exist with nature.

According to the *philosophes* of the Enlightenment, the path to complete knowledge required dissection of information on any given subject and a division of knowledge into subcategories of subcategories, known as reductionism. This was considered necessary in order to build upon the knowledge of the ancients, such as Ptolemy, and Renaissance thinkers, such as Copernicus, Kepler, and Galileo. It was widely believed that man's sheer intellectual power alone was sufficient to understanding every aspect of nature. Examples of prominent Enlightenment scholars include Sir Isaac Newton (physics and mathematics), Gottfried Leibniz (philosophy and mathematics), and Carl Linnaeus (botanist and physician).

Principles of Romanticism

Romanticism had four basic principles: "the original unity of man and nature in a Golden Age; the subsequent separation of man from nature and the fragmentation of human faculties; the interpretability of the history of the universe in human, spiritual terms; and the possibility of salvation through the contemplation of nature."

The above-mentioned Golden Age is a reference from Greek mythology and legend to the Ages of Man. Romantic thinkers sought to reunite man with nature and therefore his natural state.

To Romantics, "science must not bring about any split between nature and man." Romantics believed in the intrinsic ability of mankind to understand nature and its phenomena, much like the Enlightened *philosophes*, but they preferred not to dissect information as some insatiable thirst for knowledge and did not advocate what they viewed as the manipulation of nature. They saw the Enlightenment as the "cold-hearted attempt to extort knowledge from nature" that placed man above nature rather than as a harmonious part of it; conversely, they wanted to "improvise on nature as a great instrument." The philosophy of nature was devoted to the observation of facts and careful experimentation, which was much more of a "hands-off" approach to understanding science than the Enlightenment view, as it was considered too controlling.

Natural science, according to the Romantics, involved rejecting mechanical metaphors in favor of organic ones; in other words, they chose to view the world as composed of living beings with sentiments, rather than objects that merely function. Sir Humphry Davy, a prominent Romantic thinker, said that understanding nature required "an attitude of admiration, love and worship, ... a personal response." He believed that knowledge was only attainable by those who truly appreciated and respected nature. Self-understanding was an important aspect of Romanticism. It had less to do with proving that man was capable of understanding nature (through his budding intellect) and therefore controlling it, and more to do with the emotional appeal of connecting himself with nature and understanding it through a harmonious co-existence.

Important works in Romantic science

When categorizing the many disciplines of science that developed during this period, Romantics believed that explanations of various phenomena should be based upon *vera causa*, which meant that already known causes would produce similar effects elsewhere. It was also in this way that Romanticism was very anti-reductionist: they did not believe that inorganic sciences were at the top of the hierarchy but at the bottom, with life sciences next and psychology placed even higher. This hierarchy reflected Romantic ideals of science because the whole organism takes more precedence over inorganic matter, and the intricacies of the human mind take even more precedence since the human intellect was sacred and necessary to understanding nature around it and reuniting with it.

Various disciplines on the study of nature that were cultivated by Romanticism included: Schelling's *Naturphilosophie*; cosmology and cosmogony; developmental history of the earth and its creatures; the new science of biology; investigations of mental states, conscious and unconscious, normal and abnormal; experimental disciplines to uncover the hidden forces of nature – electricity, magnetism, galvanism and other life-forces; physiognomy, phrenology, meteorology, mineralogy, "philosophical" anatomy, among others.

Naturphilosophie

In Friedrich Schelling's *Naturphilosophie*, he explained his thesis regarding the necessity of reuniting man with nature; it was this German work that first defined the Romantic conception of science and vision of natural philosophy. He called nature "a history of the path to freedom" and encouraged a reunion of man's spirit with nature.

Biology

The "new science of biology" was first termed *biologie* by Jean-Baptiste Lamarck in 1801, and was "an independent scientific discipline born at the end of a long process of erosion of 'mechanical philosophy,' consisting in a spreading awareness that the phenomena of living nature cannot be understood in the light of the laws of physics but require an ad hoc explanation." The mechanical philosophy of the 17th century sought to explain life as a system of parts that operate or interact like those of a machine. Lamarck stated that the life sciences must detach from the physical sciences and strove to create a field of research that was different from the concepts, laws, and principles of physics. In rejecting mechanism without entirely abandoning the research of material phenomena that does occur in nature, he was able to point out that "living beings have specific characteristics which cannot be reduced to those possessed by physical bodies" and that living nature was *un ensemble d'objets métaphisiques* ("an assemblage of metaphysical objects"). He did not 'discover' biology; he drew previous works together and organized them into a new science.

Goethe

Johann Goethe's experiments with optics were the direct result of his application of Romantic ideals of observation and disregard for Newton's own work with optics. He believed that color was not an outward physical phenomenon but internal to the human; Newton concluded that white light was a mixture of the other colors, but Goethe believed he had disproved this claim by his observational experiments. He thus placed emphasis on the human ability to see the color, the human ability to gain knowledge through "flashes of insight", and not a mathematical equation that could analytically describe it.

Humboldt

Alexander von Humboldt was a staunch advocate of empirical data collection and the necessity of the natural scientist in using experience and quantification to understand nature. He sought to find the unity of nature, and his books *Aspects of Nature* and *Kosmos* lauded the aesthetic qualities of the natural world by describing natural science in religious tones. He believed science and beauty could complement one another.

Natural history

Romanticism also played a large role in Natural history, particularly in biological evolutionary theory. Nichols (2005) examines the connections between science and poetry in the English-speaking world during the 18th and 19th centuries, focusing on the works of American natural historian William Bartram and British naturalist Charles Darwin. Bartram's *Travels through North and South Carolina, Georgia, East and West Florida* (1791) described the flora, fauna, and landscapes of the American South with a cadence and energy that lent itself to mimicry and became a source of inspiration to such Romantic poets of the era as William Wordsworth, Samuel Taylor Coleridge, and William Blake. Darwin's work, including *On the Origin of Species by Means of Natural Selection* (1859), marked an end to the Romantic era, when using nature as a source of creative inspiration was commonplace, and led to the rise of realism and the use of analogy in the arts.

Mathematics

Alexander (2006) argues that the nature of mathematics changed in the 19th century from an intuitive, hierarchical, and narrative practice used to solve real-world problems to a theoretical one in which logic, rigor, and internal consistency rather than application were important. Unexpected new fields emerged, such as non-Euclidean geometry and statistics, as well as group theory, set theory and symbolic logic. As the discipline changed, so did the nature of the men involved, and the image of the tragic Romantic genius often found in art, literature, and music may also be applied to such mathematicians as Évariste Galois (1811–32), Niels Henrik Abel (1802–29), and János Bolyai (1802–60). The greatest of the Romantic mathematicians was Carl Friedrich Gauss (1777–1855), who made major contributions in many branches of mathematics.

Physics

Christensen (2005) shows that the work of Hans Christian Ørsted (1777–1851) was based in Romanticism. Ørsted's discovery of electromagnetism in 1820 was directed against the mathematically based Newtonian physics of the Enlightenment; Ørsted considered technology and practical applications of science to be unconnected with true scientific research. Strongly influenced by Kant's critique of corpuscular theory and by his friendship and collaboration with Johann Wilhelm Ritter (1776–1809), Ørsted subscribed to a Romantic natural philosophy that rejected the idea of the universal extension of mechanical principles understandable through mathematics.

For him the aim of natural philosophy was to detach itself from utility and become an autonomous enterprise, and he shared the Romantic belief that man himself and his interaction with nature was at the focal point of natural philosophy.

Astronomy

Astronomer William Herschel (1738–1822) and his sister Caroline Herschel (1750–1848), were dedicated to the study of the stars; they changed the public conception of the solar system, the Milky Way, and the meaning of the universe.

Chemistry

Sir Humphry Davy was "the most important man of science in Britain who can be described as a Romantic." His new take on what he called "chemical philosophy" was an example of Romantic principles in use that influenced the field of chemistry; he stressed a discovery of "the primitive, simple and limited in number causes of the phenomena and changes observed" in the physical world and the chemical elements already known, those having been discovered by Antoine-Laurent Lavoisier, an Enlightenment *philosophe*. True to Romantic anti-reductionism, Davy claimed that it was not the individual components, but "the powers associated with them, which gave character to substances"; in other words, not what the elements were individually, but how they combined to create chemical reactions and therefore complete the science of chemistry.

Organic chemistry

The development of organic chemistry in the 19th century necessitated the acceptance by chemists of ideas deriving from *Naturphilosophie*, modifying the Enlightenment concepts of organic composition put forward by Lavoisier. Of central importance was the work on the constitution and synthesis of organic substances by contemporary chemists.

Popular image of science

Another Romantic thinker, who was not a scientist but a writer, was Mary Shelley. Her famous book *Frankenstein* also conveyed important aspects of Romanticism in science as she included elements of anti-reductionism and manipulation of nature, both key themes that concerned Romantics, as well as the scientific fields of chemistry, anatomy, and natural philosophy. She stressed the role and responsibility of society regarding science, and through the moral of her story supported the Romantic stance that science could easily go wrong unless man took more care to appreciate nature rather than control it.

John Keats' portrayal of "cold philosophy" in the poem "Lamia" influenced Edgar Allan Poe's 1829 sonnet "To Science" and Richard Dawkins' 1998 book, *Unweaving the Rainbow*.

Decline of Romanticism

The rise of Auguste Comte's positivism in 1840 contributed to the decline of the Romantic approach to science.

Chapter 29

History of Science in Africa

Africa has the world's oldest record of human technological achievement: the oldest stone tools in the world have been found in eastern Africa, and later evidence for tool production by our hominin ancestors has been found across Sub-Saharan Africa. The history of science and technology in Africa since then has, however, received relatively little attention compared to other regions of the world, despite notable African developments in mathematics, metallurgy, architecture, and other fields.

Early humans

The Great Rift Valley of Africa provides critical evidence for the evolution of early hominins. The earliest tools in the world can be found there as well:

- An unidentified hominin, possibly *Australopithecus afarensis or Kenyanthropus platyops*, created stone tools dating to 3.3 million years ago at Lomekwi in the Turkana Basin, eastern Africa.
- *Homo habilis*, residing in eastern Africa, developed another early toolmaking industry, the Oldowan, around 2.3 million years ago.
- *Homo erectus* developed the Acheulean stone tool industry, specifically hand-axes, at 1.5 million years ago. This tool industry spread to the Middle East and

Europe around 800,000 to 600,000 years ago. *Homo erectus* also begins using fire.

- *Homo sapiens*, or modern humans, created bone tools and backed blades around 90,000 to 60,000 years ago, in southern and eastern Africa. The use of bone tools and backed blades eventually became characteristic of Later Stone Age tool industries. The first appearance of abstract art is during the Middle Stone Age, however. The oldest abstract art in the world is a shell necklace dated to 82,000 years ago from the Cave of Pigeons in Taforalt, eastern Morocco. The second oldest abstract art and the oldest rock art is found at Blombos Cave in South Africa, dated to 77,000 years ago. There are evidences that stone age humans around 100,000 years ago had an elementary knowledge of chemistry in Southern Africa, and that they used a specific recipe to create a liquefied ochre-rich mixture., according to Henshilwood "This isn't just a chance mixture, it is early chemistry. It suggests conceptual and probably cognitive abilities which are the equivalent of modern humans".

Education

Northern Africa and the Nile Valley

In 295 BC, the Library of Alexandria was founded in Egypt. It was considered the largest library in the classical world.

Al-Azhar University, founded in 970~972 as a madrasa, is the chief centre of Arabic literature and Sunni Islamic learning in the world. The oldest degree-granting university in Egypt after the Cairo University, its establishment date may be considered 1961 when non-religious subjects were added to its curriculum.

West Africa and the Sahel

Three philosophical schools in Mali existed during the country's "golden age" from the 12th to the 16th centuries: University of Sankore, Sidi Yahya University, and Djinguereber University.

By the end of Mansa Musa's reign in Mali, the Sankoré University had been converted into a fully staffed University with the largest collections of books in Africa since the Library of Alexandria. The Sankoré University was capable of housing 25,000 students and had one of the largest libraries in the world with between 400,000 and 700,000 manuscripts.

Timbuktu was a major center of book copying, religious groups, the sciences, and arts. Scholars and students came throughout world to study in its university. It attracted more foreign students than New York University.

Astronomy

Three types of calendars can be found in Africa: lunar, solar, and stellar. Most African calendars are a combination of the three. African calendars include the Akan calendar, Egyptian calendar, Berber calendar, Ethiopian calendar, Igbo calendar, Yoruba calendar, Shona calendar, Swahili calendar, Xhosa calendar, Borana calendar, and Luba calendar and Ankole calender.

Northern Africa and the Nile Valley

A stone circle located in the Nabta Playa basin may be one of the world's oldest known archeoastronomical devices. Built by the ancient Nubians about 4800 BCE, the device may have approximately marked the summer solstice.

Since the first modern measurements of the precise cardinal orientations of the Egyptian pyramids were taken by Flinders Petrie, various astronomical methods have been proposed as to how these orientations were originally established. Ancient Egyptians may have observed, for example, the positions of two stars in the Plough / Big Dipper which was known to Egyptians as the thigh. It is thought that a vertical alignment between these two stars checked with a plumb bob was used to ascertain where North lay. The deviations from true North using this model reflect the accepted dates of construction of the pyramids.

Egyptians were the first to develop a 365-day, 12 month calendar. It was a stellar calendar, created by observing the stars.

During the 12th century, the astrolabic quadrant was invented in Egypt.

West Africa and the Sahel

Based on the translation of 14 Timbuktu manuscripts, the following points can be made about Timbuktu astronomical science during the 12th–16th centuries:

- They made use of the Julian Calendar.
- Generally speaking, they had a heliocentric view of the solar system.
- Diagrams of planets and orbits made use of complex mathematical calculations.
- Scientists developed an algorithm that accurately oriented Timbuktu to Mecca.
- They recorded astronomical events, including a meteor shower in August 1583.

At this time, Mali also had a number of astronomers including the emperor and scientist Askia Mohammad I.

Eastern Africa

Megalithic "pillar sites," known as "namoratunga," date to as early as 5,000 years ago and can be found surrounding Lake Turkana in Kenya. Although somewhat controversial today, initial interpretations suggested that they were used by Cushitic speaking people as an alignment with star systems tuned to a lunar calendar of 354 days.

Southern Africa

Today, South Africa has cultivated a burgeoning astronomy community. It hosts the Southern African Large Telescope, the largest optical telescope in the southern hemisphere. South Africa is currently building the Karoo Array Telescope as a pathfinder for the $20 billion Square Kilometer Array project. South Africa is a finalist, with Australia, to be the host of the SKA.

Mathematics

Central and Southern Africa

The Lebombo bone from the mountains between Swaziland and South Africa may be the oldest known mathematical artifact. It dates from 35,000 BCE and consists of 29 distinct notches that were deliberately cut into a baboon's fibula.

The Ishango bone is a bone tool from the Democratic Republic of Congo dated to the Upper Paleolithic era, about 18,000 to 20,000 BCE. It is also a baboon's fibula, with a sharp piece of quartz affixed to one end, perhaps for engraving or writing. It was first thought to be a tally stick, as it has a series of tally marks carved in three columns running the length of the tool, but some scientists have suggested that the groupings of notches indicate a mathematical understanding that goes beyond counting. Various functions for the bone have been proposed: it may have been a tool for multiplication, division, and simple mathematical calculation, a six-month lunar calendar, or it may have been made by a woman keeping track of her menstrual cycle.

The "sona" drawing tradition of Angola also exhibit certain mathematical ideas.

In 1982, Rebecca Walo Omana became the first female mathematics professor in the Democratic Republic of the Congo.

Northern Africa and the Nile Valley

By the predynastic Naqada period in Egypt, people had fully developed a numeral system. The importance of mathematics to an educated Egyptian is suggested by a New Kingdom fictional letter in which the writer proposes a scholarly competition between himself and another scribe regarding everyday calculation tasks such as accounting of land, labor and grain. Texts such as the Rhind Mathematical Papyrus and the Moscow Mathematical Papyrus show that the ancient Egyptians could perform the four basic mathematical operations—addition, subtraction, multiplication, and division—use fractions, knew the formula to compute the volume of a frustum, and calculate the surface areas of triangles, circles and even hemispheres. They understood basic concepts of algebra and geometry, and could solve simple sets of simultaneous equations.

Mathematical notation was decimal, and based on hieroglyphic signs for each power of ten up to one million. Each of these could be written as many times as necessary to add up to the desired number; so to write the number eighty or eight hundred, the symbol for ten or one hundred was written eight times respectively. Because their methods of calculation could not handle most fractions with a numerator greater than one, ancient Egyptian fractions had to be written as the sum of several fractions. For example, the fraction two-fifths was resolved into the sum of one-third + one-fifteenth; this was facilitated by standard tables of values. Some common fractions, however, were written with a special glyph; the equivalent of the modern two-thirds is shown on the right.

Ancient Egyptian mathematicians had a grasp of the principles underlying the Pythagorean theorem, knowing, for example, that a triangle had a right angle opposite the hypotenuse when its sides were in a 3–4–5 ratio. They were able to estimate the area of a circle by subtracting one-ninth from its diameter and squaring the result:

- Area $\approx [(8/9)D] = (256/81)r \approx 3.16r$,

a reasonable approximation of the formula **π**r.

The golden ratio seems to be reflected in many Egyptian constructions, including the pyramids, but its use may have been an unintended consequence of the ancient Egyptian practice of combining the use of knotted ropes with an intuitive sense of proportion and harmony.

Based on engraved plans of Meroitic King Amanikhabali's pyramids, Nubians had a sophisticated understanding of mathematics and an appreciation of the harmonic ratio. The engraved plans is indicative of much to be revealed about Nubian mathematics.

West Africa and the Sahel

All of the mathematical learning of the Islamic world during the medieval period was available and advanced by Timbuktu scholars: arithmetic, algebra, geometry, and trigonometry.

Metallurgy

Most of sub-Saharan Africa moved from the Stone Age to the Iron Age. The Iron Age and Bronze Age occurred simultaneously. North Africa and the Nile Valley imported its iron technology from the Near East and followed the Near Eastern pattern of development from the Bronze Age to the Iron Age.

Many Africanists accept an independent development of the use of iron in Sub-Saharan Africa. Among archaeologists, it is a debatable issue. The earliest dating of iron in sub-Saharan Africa is 2500 BCE at Egaro, west of Termit, making it contemporary with iron smelting in the Middle East. The Egaro date is debatable with archaeologists, due to the method used to attain it. The Termit date of 1500 BCE is widely accepted. Iron at the site of Lejja, Nigeria, has been radiocarbon dated to approximately 2000 BC. Iron use, in smelting and forging for tools, appears in West Africa by 1200 BCE, making it one of the first places for the birth of the Iron Age. Before the 19th century, African methods of extracting iron were employed in Brazil, until more advanced European methods were instituted.

West Africa

Besides being masters in iron, Africans were masters in brass and bronze. Ife produced lifelike statues in brass, an artistic tradition beginning in the 13th century. Benin mastered bronze during the 16th century, produced portraiture and reliefs in the metal using the lost wax process. Benin also was a manufacturer of glass and glass beads.

In West Africa several centres of iron production using natural draft furnaces emerged from the early second millennium AD. Iron production in Banjeli and Bassar for example in Togo reached up to 80,000 cubic meters(which is more than the production at places such as Meroe), analyses indicate that fifteenth-and sixteenth-century AD slags from this area were just bloomery waste products, while preliminary metallographic analyses of objects indicate them to be made of low-carbon steels. In Burkina Faso, the Korsimoro district reached up to 169,900 cubic meters. In the Dogon region, the sub-region of Fiko has about 300,000 cubic meters of slag produced.

Brass barrel blunderbuss are said to have been produced in some states of the Gold Coast in the eighteenth and nineteenth centuries. Various accounts indicate that Asante blacksmiths were not only able to repair firearms, but that barrels, locks and stocks were on occasion remade.

In the Aïr Mountains region of Niger, copper smelting was independently developed between 3000 and 2500 BCE. The undeveloped nature of the process indicates that it was not of foreign origin. Smelting in the region became mature around 1500 BCE.

The Sahel

Africa was a major supplier of gold in world trade during the Medieval Age. The Sahelian empires became powerful by controlling the Trans-Saharan trade routes. They provided 2/3 of the gold in Europe and North Africa. The Almoravid dinar and the Fatimid dinar were printed on gold from the Sahelian empires. The ducat of Genoa and Venice and the florine of Florence were also printed on gold from the Sahelian empires. When gold sources were depleted in the Sahel, the empires turned to trade with the Ashanti Empire.

The Swahili traders in East Africa were major suppliers of gold to Asia in the Red Sea and Indian Ocean trade routes. The trading port cities and city-states of the Swahili East African coast were among the first African cities to come into contact with European explorers and sailors during the European Age of Discovery. Many were documented and praised in the recordings of North African explorer Abu Muhammad ibn Battuta.

Northern Africa and the Nile Valley

Nubia was a major source of gold in the ancient world. Gold was a major source of Kushitic wealth and power. Gold was mined East of the Nile in Wadi Allaqi and Wadi Cabgaba.

Around 500 BCE, Nubia, during the Meroitic phase, became a major manufacturer and exporter of iron. This was after being expelled from Egypt by Assyrians, who used iron weapons.

East Africa

The Aksumites produced coins around 270 CE, under the rule of King Endubis. Aksumite coins were issued in gold, silver, and bronze.

Since 500 BC, Bantu peoples in Uganda had been producing high grade carbon steels using preheated forced draft furnaces, a technique achieved in europe only with the siemons process in the mid 19th century. Anthropologist Peter Schmidt discovered through the communication of oral tradition that the Haya in Tanzania have been forging steel for nearly 2000 years. This discovery was made accidentally while Schmidt was learning about the history of the Haya via their oral tradition. He was led to a tree which was said to rest on the spot of an ancestral furnace used to forge steel. When later tasked with the challenge of recreating the forges, a group of elders who at this time were the only ones to remember the practice, due to the disuse of the practice due in part to the abundance of steel flowing into the country from foreign sources. In spite of their lack of practice, the elders were able to create a furnace using mud and grass which when burnt provided the carbon needed to transform the iron into steel. Later investigation of the area yielded 13 other furnaces similar in design to the recreation set up by the elders. These furnaces were carbon dated and were found to be as old as 2000 years, whereas steel of this caliber did not appear in Europe until several centuries later.

Two types of iron furnaces were used in Sub-Saharan Africa: the trench dug below ground and circular clay structures built above ground. Iron ores were crushed and placed in furnaces layered with the right proportion of hardwood. A flux such as lime sometimes from seashells was added to aid in smelting. Bellows on the side would be used to add oxygen. Clay pipes on the sides called tuyères would be used to control oxygen flow.

Medicine

West Africa and the Sahel

The knowledge of inoculating oneself against smallpox seems to have been known to West Africans, more specifically the Akan. A slave named Onesimus explained the inoculation procedure to Cotton Mather during the 18th century; he reported to have gotten the knowledge from Africa.

Bonesetting is practiced by many groups of West Africa (the Akan, Mano, and Yoruba, to name a few).

In Djenné the mosquito was identified to be the cause of malaria, and the removal of cataracts was a common surgical procedure (as in many other parts of Africa). The dangers of tobacco smoking were known to African Muslim scholars, based on Timbuktu manuscripts.

Northern Africa and the Nile Valley

Ancient Egyptian physicians were renowned in the ancient Near East for their healing skills, and some, like Imhotep, remained famous long after their deaths. Herodotus remarked that there was a high degree of specialization among Egyptian physicians, with some treating only the head or the stomach, while others were eye-doctors and dentists. Training of physicians took place at the *Per Ankh* or "House of Life" institution, most notably those headquartered in Per-Bastet during the New Kingdom and at Abydos and Saïs in the Late period. Medical papyri show empirical knowledge of anatomy, injuries, and practical treatments. Wounds were treated by bandaging with raw meat, white linen, sutures, nets, pads and swabs soaked with honey to prevent infection, while opium was used to relieve pain. Garlic and onions were used regularly to promote good health and were thought to relieve asthma symptoms. Ancient Egyptian surgeons stitched wounds, set broken bones, and amputated diseased limbs, but they recognized that some injuries were so serious that they could only make the patient comfortable until he died.

Around 800, the first psychiatric hospital and insane asylum in Egypt was built by Muslim physicians in Cairo.

Around 1100, the ventilator is invented in Egypt.

In 1285, the largest hospital of the Middle Ages and pre-modern era was built in Cairo, Egypt, by Sultan Qalaun al-Mansur. Treatment was given for free to patients of all backgrounds, regardless of gender, ethnicity or income.

Tetracycline was being used by Nubians, based on bone remains between 350 AD and 550 AD. The antibiotic was in wide commercial use only in the mid 20th century. The theory is earthen jars containing grain used for making beer contained the bacterium streptomycedes, which produced tetracycline. Although Nubians were not aware of tetracycline, they could have noticed people fared better by drinking beer. According to Charlie Bamforth, a professor of biochemistry and brewing science at the University of California, Davis, said "They must have consumed it because it was rather tastier than the grain from which it was derived. They would have noticed people fared better by consuming this product than they were just consuming the grain itself."

East Africa

European travelers in the Great Lakes region of Africa during the 19th century reported cases of surgery in the kingdom of Bunyoro-Kitara. Medical historians, such as Jack Davies argued in 1959 that Bunyoro's traditional healers were perhaps the most highly skilled in pre-colonial sub- Saharan Africa, possessing a remarkable level of medical knowledge. One observer noted a "surgical skill which had reached a high standard". Caesarean sections and other abdominal and thoracic operations were performed on a regular basis with the avoidance of haemorrhage and sepsis using antiseptics, anaesthetics and cautery iron. The expectant mother was normally anesthetized with banana wine, and herbal mixtures were used to encourage healing. From the well-developed nature of the procedures employed, European observers concluded that they had been employed for some time. Bunyoro surgeons treated lung inflammations and pleurisy by punching holes in the chest until the air passed freely. Trephining was carried out and the bones of depressed fractures were elevated. Horrible war wounds, even penetrating abdominal and chest wounds were treated with success, even when this involved quite heroic surgery. The Banyoro surgeons had a good knowledge of anatomy, in part obtained by carrying out autopsies. Inoculation against smallpox and even measles was carried out in Bunyoro and its neighbouring kingdoms. Over 200 plants are used medicinally in eastern Bunyoro alone and recent tests have shown that traditional cures for eczema and post-measles bloody diarrhoea were more effective than western medications. Bunyoro's Medical elite, the "Bafumu", had a system of apprenticeship and even "met at periods for conferences".. Barkcloth, which was used to bandage wounds, has been proven to be antimicrobial.

Brain surgery was also practiced in the Great lakes region of africa

Southern Africa

A South African, Max Theiler, developed a vaccine against yellow fever in 1937. Allan McLeod Cormack developed the theoretical underpinnings of CT scanning and co-invented the CT-scanner.

The first human-to-human heart transplant was performed by South African cardiac surgeon Christiaan Barnard at Groote Schuur Hospital in December 1967. See also Hamilton Naki.

During the 1960s, South African Aaron Klug developed crystallographic electron microscopy techniques, in which a sequence of two-dimensional images of crystals taken from different angles are combined to produce three-dimensional images of the target.

Agriculture

Northern Africa and the Nile Valley

Archaeologists have long debated whether or not the independent domestication of cattle occurred in Africa as well as the Near East and Indus Valley. Possible remains of domesticated cattle were identified in the Western Desert of Egypt at the sites of Nabta Playa and Bir Kiseiba and were dated to c. 9500–8000 BP, but those identifications have been questioned. Genetic evidence suggests that cattle were most likely introduced from Southwest Asia, and that there may have been some later breeding with wild aurochs in northern Africa.

Genetic evidence also indicates that donkeys were domesticated from the African wild ass. Archaeologists have found donkey burials in early Dynastic contexts dating to ~5000 BP at Abydos, Middle Egypt, and examination of the bones shows that they were used as beasts of burden.

Cotton (*Gossypium herbaceum* Linnaeus) may have been domesticated 5000 BCE in eastern Sudan near the Middle Nile Basin region, where cotton cloth was being produced.

East Africa

Engaruka is an Iron Age archaeological site in northern Tanzania known for the ruins of a complex irrigation system. Stone channels were used to dike, dam, and level surrounding river waters. Some of these channels were several kilometers long, channelling and feeding individual plots of land totaling approximately 5,000 acres (20 km). Seven stone-terraced villages along the mountainside also comprise the settlement.

The Shilluk Kingdom gained control of the west bank of the white Nile as far north as Kosti in Sudan. There they established an economy based on cereal farming and fishing, with permanent settlements located along the length of the river. The Shilluk developed an extremely intensive system of agriculture based off of Sorghum, Millet and other crops. By the 1600's, shillukland had a population density similar or exceeding that of the Egyptian Nile landsThe explorer Geerge Sweinfurth, who was not prone to exaggeration wrote of his 1869 visit to Shillukland:

No known part of Africa, scarcely even the narrow valley of the Nile in Egypt, has a density of population so great; but a similar condition of circumstances, so favorable to the support of a teeming population, is perhaps without parallel in the world. Everything which contributes to the exuberance of life here finds a concentrated field-agriculture, pasturage, fishing, and the chase. Agriculture is rendered easy by the natural fertility of the soil, by the recurrence of the rainy

seasons, by irrigation, effected by an atmosphere ordinarily so overclouded as to moderate the radiance of the sun, and so retain throughout the year perpetual moisture.

- *—L. Lewis Wall, Anuak Politics, Ecology, and the Origins of Shilluk Kingship (1976)*

Ethiopians, particularly the Oromo people, were the first to have discovered and recognized the energizing effect of the coffee bean plant.

Ox-drawn plows seems to have been used in Ethiopia for two millennia, and possibly much longer. Linguistic evidences suggests that the Ethiopian plow might be the oldest plow in Africa.

Teff is believed to have originated in Ethiopia between 4000 and 1000 BCE. Genetic evidence points to *E. pilosa* as the most likely wild ancestor. Noog (*Guizotia abyssinica*) and ensete (*E. ventricosum*) are two other plants domesticated in Ethiopia.

Ethiopians used terraced hillside cultivation for erosion prevention and irrigation. A 19th century European described Yeha:

All the surrounding hills have been terraced for cultivation, and present much the same appearance as the hills in Greece and Asia Minor, which have been neglected for centuries; but nowhere in Greece or Asia Minor have I ever seen such an enormous extent of terraced mountains as in this Abyssinian valley. Hundreds and thousands of acres must here have been under the most careful cultivation, right up almost to the tops of the mountains, and now nothing is left but the regular lines of the sustaining walls, and a few trees dotted about here and there. This valley is most completely shut in, quite such an one as one can imagine Rasselas to have lived in

- *—James T. Bent, The sacred city of the Ethiopians, being a record of travel and research in Abyssinia in 1893 (1896)*

within the African Great Lakes advanced agriculture practices were employed such as "hydraulic practices in the mountains man-made watering places, river diversions, hollowed-out tree-trunk pipes, irrigation on cultivated slopes, mounding in drained marshes, and irrigation of banana and palm tree gardens" as well as extensive use of terraces. Europeans travelers described the agricultural landscape of the great lakes below:

The beautifully irrigated fields, the steep terraced slopes of the thousand hills, where every patch of ground is put to use, the well fed cattle with colossal horns were wonderful discoveries to the Europeans. But even greater surprises awaited them.

- *—Christian P. Scherre, Genocide and Crisis in Central Africa: Conflict Roots, Mass Violence, and Regional War (2001)*

West Africa and the Sahel

The earliest evidence for the domestication of plants for agricultural purposes in Africa occurred in the Sahel region c. 5000 BCE, when sorghum and African rice (*Oryza glaberrima*) began to be cultivated. Around this time, and in the same region, the small guineafowl was domesticated. Other African domesticated plants were oil palm, raffia palm, black-eyed peas, groundnuts, and kola nuts.

African methods of cultivating rice, introduced by enslaved Africans, may have been used in North Carolina. This may have been a factor in the prosperity of the North Carolina colony. Portuguese observers between the half of the 15th century and the 16th century witnessed the cultivation of rice in the Upper Guinea Coast, and admired the local rice-growing technology, as it involved intensive agricultural practices such as diking and transplanting.

Yams were domesticated 8000 BCE in West Africa. Between 7000 and 5000 BCE, pearl millet, gourds, watermelons, and beans also spread westward across the southern Sahara.

Between 6500 and 3500 BCE knowledge of domesticated sorghum, castor beans, and two species of gourd spread from Africa to Asia. Pearl millet, black-eyed peas, watermelon, and okra later spread to the rest of the world.

In the lack of more detailed historical and archaeological studies on the chronology of terracing, intensive terrace farming is believed to have been practiced before the early 15th century AD in West Africa. Terraces were used by many groups, notably the Mafa, Ngas, Gwoza, and the Dogon.

Southern Africa

Randall-MacIver described the irrigation technology used in Nyanga, Zimbabwe :

The country about Inyanga is well watered, but it would seem that the old inhabitants required a more general distribution of the supply than was afforded by the numerous streams running down from the hills. Accordingly, they adopted a practice which has been prevalent under similar conditions in several other countries, Algeria being one instance which has come under the waiter's own observation. The stream was tapped at a point near its source, and part of the water deflected by a stone dam. This gave them a high-level conduit, by which the water could be carried along the side of a hill and allowed to descend more gradually than the parent stream. There are very many such conduits in the Inyanga region, and they often run for several miles. The gradients are admirably calculated, with a skill which is not always equalled by modern engineers with their elaborate instruments. The dams are well and strongly built of unworked stones without mortar; the conduits themselves are simple trenches about one metre in depth. The earth taken out of the trench is piled on its lower side and supported by boulders imbedded in ito.

Textiles

Northern Africa

Egyptians wore linen from the flax plant, and used looms as early as 4000 BCE. Nubians mainly wore cotton, beaded leather, and linen. The Djellaba was made typically of wool and worn in the Maghreb.

West Africa and the Sahel

Some of the oldest surviving African textiles were discovered at the archaeological site of Kissi in northern Burkina Faso. They are made of wool or fine animal hair in a weft-faced plain weave pattern. Fragments of textile have also survived from the thirteenth century Benin City in Nigeria.

In the Sahel, cotton is widely used in making the boubou (for men) and kaftan (for women).

Bògòlanfini (mudcloth) is cotton textile dyed with fermented mud of tree sap and teas, hand made by the Bambara people of the Beledougou region of central Mali.

By the 12th century, so-called Moroccan leather, which actually came from the Hausa area of northern Nigeria, was supplied to Mediterranean markets and found their way to the fairs and markets of Europe

Kente was produced by the Akan people (Ashante, Fante, Enzema) and Ewe people in the countries of Togo, Ghana and Côte d'Ivoire.

Central Africa

Among Kuba people, in present day Democratic Republic of Congo, raffia clothes were weaved. They used the fibers of the leaves on the raffia palm tree.

East Africa

Barkcloth was used by the Baganda in Uganda from the Mutuba tree (*Ficus natalensis*). Kanga are Swahili pieces of fabric that come in rectangular shapes, made of pure cotton, and put together to make clothing. It is as long as ones outstretch hand and wide to cover the length of ones neck. Kitenge are similar to kangas and kikoy, but are of a thicker cloth, and have an edging only on a long side. Kenya, Uganda, Tanzania, and Sudan are some of the African countries where kitenge are worn. In Malawi, Namibia and Zambia, kitenge are known as Chitenge. Lamba Mpanjaka was cloth made of multicolored silk, worn like a toga on the island of Madagascar.

Shemma, shama, and kuta are all cotton-based cloths used for making Ethiopian clothing. Three types of looms are used in Africa: the double heddle loom for narrow strips of cloth, the single heddle loom for wider spans of cloth, and the ground or pit loom. The double heddle loom and single heddle loom might be of African origin. The ground or pit loom is used in the Horn of Africa, Madagascar, and North Africa and is of Middle Eastern origins.

Southern Africa

In southern Africa one finds numerous use of animal hide and skins for clothing. The Ndau in central Mozambique and the Shona mixed hide with barkcloth and cotton cloth. Cotton weaving was practiced by the Ndau and Shona. Cotton cloth was referred to as machira. The Venda, Swazi, Basotho, Zulu, Ndebele, and Xhosa also made extensive use of hides. Hides came from cattle, sheep, goat, elephant, and from jangwa(part of the mongoose family). Leopard skins were coveted and was a symbol of kingship in Zulu society. Skins were tanned to form leather, dyed, and embedded with beads.

Maritime technology

In 1987 the third oldest canoe in the world and the oldest in Africa, the Dufuna canoe, was discovered in Nigeria by Fulani herdsmen near the Yobe river and the village of Dufuna. It dates to approximately 8000 years ago, and was made from African mahogany.

Northern Africa and the Nile Valley

Carthage's fleet included large numbers of quadriremes and quinqueremes, warships with four and five ranks of rowers. Its ships dominated the Mediterranean. The Romans however were masters at copying and adapting the technology of other peoples. According to Polybius, the Romans seized a shipwrecked Carthaginian warship, and used it as a blueprint a massive naval build-up, adding their own refinement – the corvus – which allowed an enemy vessel to be "gripped" and boarded for hand-to-hand fighting. This negated initially superior Carthaginian seamanship and ships.

Early Egyptians knew how to assemble planks of wood into a ship hull as early as 3000 BC (5000 BCE). The oldest ships yet unearthed, a group of 14 discovered in Abydos, were constructed from wooden planks which were "sewn" together.

Woven straps were used to lash the planks together, and reeds or grass stuffed between the planks helped to seal the seams. Because the ships are all buried together and near a mortuary complex belonging to Pharaoh Khasekhemwy, originally the boats were all thought to have belonged to him. One of the 14 ships dates to 3000 BC, however, and is now thought to perhaps have belonged to an earlier pharaoh, possibly Pharaoh Aha.

West Africa and the Sahel

In the 14th century CE King Abubakari II, the brother of King Mansa Musa of the Mali Empire is thought to have had a great armada of ships sitting on the coast of West Africa. This is corroborated by ibn Battuta himself who recalls several hundred Malian ships off the coast. The ships would communicate with each other by drums.

Numerous sources attest that the inland waterways of West Africa saw extensive use of war-canoes and vessels used for war transport where permitted by the environment. Most West African canoes were of single log construction, carved and dug-out from one massive tree trunk. The primary method of propulsion was by paddle and in shallow water, poles. Sails were also used to a lesser extent, particularly on trading vessels. The silk cotton tree provided many of the most table logs for massive canoe building, and launching was via wooden rollers to the water. Boat building specialists were to emerge among certain peoples, particularly in the Niger Delta.

Some canoes were 80 feet (24 m) in length, carrying 100 men or more. Documents from 1506 for example, refer to war-canoes on the Sierra Leone river, carrying 120 men. Others refer to Guinea coast peoples using canoes of varying sizes – some 70 feet (21 m) in length, 7–8 ft broad, with sharp pointed ends, rowing benches on the side, and quarter decks or focastles build of reeds, and miscellaneous facilities such as cooking hearths, and storage spaces for crew sleeping mats.

Early Egyptians also knew how to assemble planks of wood with treenails to fasten them together, using pitch for caulking the seams. The "Khufu ship", a 43.6-meter vessel sealed into a pit in the Giza pyramid complex at the foot of the Great Pyramid of Giza in the Fourth Dynasty around 2500 BCE, is a full-size surviving example which may have fulfilled the symbolic function of a solar barque. Early Egyptians also knew how to fasten the planks of this ship together with mortise and tenon joints.

East Africa

It is known that ancient Axum traded with India, and there is evidence that ships from Northeast Africa may have sailed back and forth between India/Sri Lanka and Nubia trading goods and even to Persia, Himyar and Rome. Aksum was known by the Greeks for having seaports for ships from Greece and Yemen. Elsewhere in Northeast Africa, the 1st century CE Greek travelogue *Periplus of the Red Sea* reports that Somalis, through their northern ports such as Zeila and Berbera, were trading frankincense and other items with the inhabitants of the Arabian Peninsula as well as with the then Roman-controlled Egypt.

Middle Age Swahili kingdoms are known to have had trade port islands and trade routes with the Islamic world and Asia and were described by Greek historians are "metropolises". Famous African trade ports such as Mombasa, Zanzibar, Mogadishu and Kilwa were known to Chinese sailors such as Zheng He and medieval Islamic historians such as the Berber Islamic voyager Abu Abdullah ibn Battuta. The dhow was the ship of trade used by the Swahili. They could be massive. It was a dhow that transported a giraffe to Chinese Emperor Yong Le's court, in 1414.

Architecture

West Africa

The Walls of Benin City are collectively the world's largest man-made structure and were semi-destroyed by the British in 1897. Fred Pearce wrote in New Scientist:

- "They extend for some 16,000 kilometres in all, in a mosaic of more than 500 interconnected settlement boundaries. They cover 6500 square kilometres and were all dug by the Edo people. In all, they are four times longer than the Great Wall of China, and consumed a hundred times more material than the Great Pyramid of Cheops. They took an estimated 150 million hours of digging to construct, and are perhaps the largest single archaeological phenomenon on the planet."

Sungbo's Eredo is the second largest pre-colonial monument in Africa, larger than the Great Pyramids or Great Zimbabwe. Built by the Yoruba people in honour of one of their titled personages, an aristocratic widow known as the Oloye Bilikisu Sungbo, it is made up of sprawling mud walls and the valleys that surrounded the town of Ijebu-Ode in Ogun state, Nigeria.

Tichit is the oldest surviving archaeological settlements in the Sahel and is the oldest all-stone settlement south of the Sahara. It is thought to have been built by Soninke people and is thought to be the precursor of the Ghana empire.

The Great Mosque of Djenné is the largest mud brick or adobe building in the world and is considered by many architects to be the greatest achievement of the Sudano-Sahelian architectural style, albeit with definite Islamic influences.

Northern Africa and the Nile Valley

Around 1000 AD, cob (tabya) first appears in the Maghreb and al-Andalus.

The Egyptian step pyramid built at Saqqara is the oldest major stone building in the world.

The Great Pyramid was the tallest man-made structure in the world for over 3,800 years.

The earliest style of Nubian architecture included the speos, structures carved out of solid rock, an A-Group (3700–3250 BCE) achievement. Egyptians made extensive use of the process at Speos Artemidos and Abu Simbel.

Sudan, site of ancient Nubia, has more pyramids than anywhere in the world, even more than Egypt, with 223 pyramids.

East Africa

Aksumites built in stone. Monolithic stelae on top of the graves of kings like King Ezana's Stele. Later, during the Zagwe Dynasty Churches carved out of solid rocks like Church of Saint George at Lalibela.

Thimlich Ohinga, a world heritage site is a complex of stone-built ruins located in Kenya.

Southern Africa

In southern Africa one finds ancient and widespread traditions of building in stone. Two broad categories of these traditions have been noted: 1. Zimbabwean style 2. Transvaal Free State style. North of the Zambezi one finds very few stone ruins. Great Zimbabwe, Khami, and Thulamela uses the Zimbabwean style. Tsotho/Tswana architecture represents the Transvaal Free State style. ||Khauxa!nas stone settlement in Namibia represents both traditions. The Kingdom of Mapungubwe (1075–1220) was a pre-colonial Southern African state located at the confluence of the Shashe and Limpopo rivers which marked the center of a pre-Shona kingdom which preceded the culmination of southeast African urban civilization in Great Zimbabwe.

Communication systems

Griots are repositories of African history, especially in African societies with no written language. Griots can recite genealogies going back centuries. They recite epics that reveal historical occurrences and events. Griots can go for hours and even days reciting the histories and genealogies of societies. They have been described as living history books.

Northern Africa and the Nile Valley

Africa's first writing system and the beginning of the alphabet was Egyptian hieroglyphs. Two scripts have been the direct offspring of Egyptian hieroglyphs, the Proto-Sinaitic script and the Meroitic alphabet. Out of Proto-Sinaitic came the South Arabian alphabet and Phoenician alphabet, out of which the Aramaic alphabet, Greek alphabet, the Brāhmī script, Arabic alphabet were directly or indirectly derived.

Out of the South Arabian alphabet came the Ge'ez alphabet which is used to write Blin(cushitic), Amharic, Tigre, and Tigrinya in Ethiopia and Eritrea.

Out the Phoenician Alphabet came tifinagh, the berber alphabet mainly used by the Tuaregs.

The other direct offspring of Egyptian hieroglyphs was the Meroitic alphabet. It began in the Napatan phase of Nubian history, Kush (700–300 BCE). It came into full fruition in the 2nd century, under the successor Nubian kingdom of Meroë. The script can be read but not understood, with the discovery at el-Hassa, Sudan of ram statues bearing meroitic inscriptions might assist in its translation.

The Sahel

With the arrival of Islam, came the Arabic alphabet in the Sahel. Arabic writing is widespread in the Sahel. The Arabic script was also used to write native African languages. The script used in this capacity is often called Ajami. The languages that have been or are written in Ajami include Hausa, Mandinka, Fulani, Wolofal, Tamazight, Nubian, Yoruba, Songhai, and Kanuri.

West Africa

N'Ko script developed by Solomana Kante in 1949 as a writing system for the Mande languages of West Africa. It is used in Guinea, Côte d'Ivoire, Mali, and neighboring countries by a number of speakers of Manding languages.

Nsibidi is ideographic set of symbols developed by the Ekoi people of Southeastern coastal Nigeria for communication. A complex implementation of Nsibidi is only known to initiates of Ekpe secret society.

Adinkra is a set of symbols developed by the Akan (Ghana and Cote d'Ivoire), used to represent concepts and aphorisms.

The Vai syllabary is a syllabic writing system devised for the Vai language by Mɔmɔlu Duwalu Bukɛlɛ in Liberia during the 1830s.

Adamorobe Sign Language is an indigenous sign language developed in the Adamorobe Akan village in Eastern Ghana. The village has a high incident of genetic deafness.

Central Africa

Across eastern Angola and northwestern Zambia, sona ideographs were used as mnemonic devices to record knowledge and culture. Lukasa memory boards were also used among the BaLuba.

Talking drums exploit the tonal aspect of many african languages to convey very complicated messages. Talking drums can send messages 15 to 25 miles (40 km). Bulu, a Bantu language, can be drummed as well as spoken. In a Bulu village, each individual had a unique drum signature. A message could be sent to an individual by drumming his drum signature. It has been noted that a message can be sent 100 miles (160 km) from village to village within two hours or less using a talking drum.

East Africa

On the Swahili coast, the Swahili language was written in Arabic script, as was the Malagasy language in Madagascar.

The people of Uganda developed a form of writing based on a floral codeand the use of talking drums was widespread as well.

Warfare

Most of tropical Africa did not have a cavalry. Horses would be wiped out by tse-tse fly. The zebra was never domesticated. The army of tropical Africa consisted of mainly infantry. Weapons included bows and arrows with low bow strength that compensated with poison-tipped arrows. Throwing knives were made use of in central Africa, spears that could double as thrusting cutting weapons, and swords were also in use. Heavy clubs when thrown could break bones, battle axe, and shields of various sizes were in widespread use. Later guns, muskets such as flintlock, wheelock, and matchlock. Contrary to popular perception, guns were also in widespread use in Africa. They typically were of poor quality, a policy of European nations to provide poor quality merchandise. One reason the slave trade was so successful was the widespread use of guns in Africa.

West Africa

Fortification was a major part of defense, integral to warfare. Massive earthworks were built around cities and settlements in West Africa, typically defended by soldiers with bow and poison-tipped arrows. The earthworks are some of the largest man made structures in Africa and the world such as the walls of Benin and Sungbo's Eredo. In Central Africa, the Angola region, one find preference for ditches, which were more successful for defense against wars with Europeans.

African infantry did not just include men. The state of Dahomey included all-female units, the so-called Dahomey

Amazons, who were personal bodyguards of the king. The Queen Mother of Benin had her own personal army, 'The Queen's Own.'

Biologicals were extensively used in many parts of Africa, most of the time in the form of poisoned arrows, but also powder spread on the war front or in the form of the poisoning of horses and water supply of the opponents. In Borgu, there were specific mixtures to kill, for hypnosis, to make the enemy bold, and to act as an antidote against the enemies' poison. A specific class of medicine-men was responsible for the making of the biologicals. In South Sudan, the people of the Koalit Hills kept their country free of Arab invasions by using tsetse flies as a weapon of war. Several accounts can give us an idea of the efficiency of the biologicals. For example, Mockley-Ferryman in 1892 commented on the Dahomean invasion of Borgu, that "their (Borgawa) poisoned arrows enabled them to hold their own with the forces of Dahomey notwithstanding the latter's muskets." The same scenario happened to Portuguese raiders in Senegambia when they were defeated by Mali's Gambian forces, and to John Hawkins in Sierra Leone where he lost a number of his men to poisoned arrows.

Northern Africa, Nile Valley, and the Sahel

Ancient Egyptian weaponry includes bows and arrow, maces, clubs, scimitars, swords, shields, and knives. Body armor was made of bands of leathers and sometimes laid with scales of copper. Horse-drawn chariots were used to deliver archers into the battle field. Weapons were initially made with stone, wood, and copper, later bronze, and later iron.

In 1260, the first portable hand cannons (midfa) loaded with explosive gunpowder, the first example of a handgun and portable firearm, were used by the Egyptians to repel the Mongols at the Battle of Ain Jalut. The cannons had an explosive gunpowder composition almost identical to the ideal compositions for modern explosive gunpowder. They were also the first to use dissolved talc for fire protection, and they wore fireproof clothing, to which Gunpowder cartridges were attached.

Aksumite weapons were mainly made of iron: iron spears, iron swords, and iron knives called poniards. Shields were made of buffalo hide. In the latter part of the 19th century, Ethiopia made a concerted effort to modernize her army. She acquired repeating rifles, artillery, and machine guns. This modernization facilitated the Ethiopian victory over the Italians at the Tigray town of Adwa in the 1896 Battle of Adwa. Ethiopia was one of the few African countries to use artillery in colonial wars.

There are also a breastplate armor made of the horny back plates of crocodile from Egypt, which was given to the Pitt Rivers Museum as part of the archaeological Founding Collection in 1884.

The first use of cannons as siege machine at the siege of Sijilmasa in 1274, according to 14th-century historian Ibn Khaldun.

The Sahelian military consisted of cavalry and infantry. Cavalry consisted of shielded, mounted soldiers. Body armor was chain mail or heavy quilted cotton. Helmets were made of leather, elephant, or hippo hide. Imported horses were shielded. Horse armor consisted of quilted cotton packed with kapok fiber and copper face plate. The stirrups could be used as weapon to disembowel enemy infantry or mounted soldiers at close range. Weapons included the sword, lance, battle-axe, and broad-bladed spear. The infantry were armed with bow and iron tipped arrows. Iron tips were usually laced with poison, from the West African plant *Strophantus hispidus*. Quivers of 40–50 arrows would be carried into battle. Later, muskets were introduced.

Southern Africa

At the Battle of Isandhlawana on 22 January 1879, the Zulu army defeated British invading troops.

From the 1960s to the 1980s, South Africa pursued research into weapons of mass destruction, including nuclear, biological, and chemical weapons. Six nuclear weapons were assembled. With the anticipated changeover to a majority-elected government in the 1990s, the South African government dismantled all of its nuclear weapons, the first nation in the world which voluntarily gave up nuclear arms it had developed itself.

Commerce

Numerous metal objects and other items were used as currency in Africa. They are as follows: cowrie shells, salt, gold (dust or solid), copper, ingots, iron chains, tips of iron spears, iron knives, cloth in various shapes (square, rolled, etc.). Copper was as valuable as gold in Africa. Copper was not as widespread and more difficult to acquire, except in Central Africa, than gold. Other valuable metals included lead and tin. Salt was also as valuable as gold. Because of its scarcity, it was used as currency.

Northern Africa and the Nile Valley

Carthage imported gold, copper, ivory, and slaves from tropical Africa. Carthage exported salt, cloth, metal goods. Before camels were used in the trans-Saharan trade pack animals, oxen, donkeys, mules, and horses were utilized. Extensive use of camels began in the 1st century CE. Carthage minted gold, silver, bronze, and electrum(mix gold and silver) coins mainly for fighting wars with Greeks and Romans. Most of their fighting force were mercenaries, who had to be paid.

Islamic North Africa made use of the Almoravid dinar and Fatimid dinar, gold coins. The Almoravid dinar and the Fatimid dinar were printed on gold from the Sahelian empires. The ducat of Genoa and Venice and the florine of Florence were also printed on gold from the Sahelian empires.

Ancient Egypt imported ivory, gold, incense, hardwood, and ostrich feather.

Nubia exported gold, cotton/cotton cloth, ostrich feathers, leopard skins, ivory, ebony, and iron/iron weapons.

West Africa and the Sahel

Cowries have been used as currency in West Africa since the 11th century when their use was first recorded near Old

Ghana. Its use may have been much older. Sijilmasa in present-day Morocco seems to be a major source of cowries in the trans-Saharan trade. In western Africa, shell money was usual tender up until the middle of the 19th century. Before the abolition of the slave trade there were large shipments of cowry shells to some of the English ports for reshipment to the slave coast. It was also common in West Central Africa as the currency of the Kingdom of Kongo called locally nzimbu. As the value of the cowry was much greater in West Africa than in the regions from which the supply was obtained, the trade was extremely lucrative. In some cases the gains are said to have been 500%. The use of the cowry currency gradually spread inland in Africa. By about 1850 Heinrich Barth found it fairly widespread in Kano, Kuka, Gando, and even Timbuktu. Barth relates that in Muniyoma, one of the ancient divisions of Bornu, the king's revenue was estimated at 30,000,000 shells, with every adult male being required to pay annually 1000 shells for himself, 1000 for every pack-ox, and 2000 for every slave in his possession. In the countries on the coast, the shells were fastened together in strings of 40 or 100 each, so that fifty or twenty strings represented a dollar; but in the interior they were laboriously counted one by one, or, if the trader were expert, five by five. The districts mentioned above received their supply of kurdi, as they were called, from the west coast; but the regions to the north of Unyamwezi, where they were in use under the name of simbi, were dependent on Muslim traders from Zanzibar. The shells were used in the remoter parts of Africa until the early 20th century, but gave way to modern currencies. The shell of the land snail, *Achatina monetaria*, cut into circles with an open center was also used as coin in Benguella, Portuguese West Africa.

The Ghana Empire, Mali Empire, and Songhay Empire were major exporters of gold, iron, tin, slaves, spears, javelin, arrows, bows, whips of hippo hide. They imported salt, horses, wheat, raisins, cowries, dates, copper, henna, olives, tanned hides, silk, cloth, brocade, Venetian pearls, mirrors, and tobacco.

Some of the currencies used in the Sahel included paper debt or IOU's for long distance trade, gold coins, and the mitkal (gold dust) currency. Gold dust that weighed 4.6 grams was equivalent to 500 or 3,000 cowries. Square cloth, four spans on each side, called chigguiya was used around the Senegal River.

In Kanem cloth was the major currency. A cloth currency called dandi was also in widespread use.

The Akan used goldweight that they called "Sika-yôbwê"(stone of gold) as their currency. They used a system of computing weight consisting of 11 units. The value of the weight were also numerically represented using two signs.

East Africa

Aksum exported ivory, glass crystal, brass, copper, myrrh, and frankincense. The Aksumites imported silver, gold, olive oil, and wine. The Aksumites produced coins around 270 CE, under the rule of king Endubis. Aksumite coins were issued in gold, silver, and bronze.

The Swahili served as middlemen. They connected African goods to Asian markets and Asian goods to African markets.

Their most in demand export was Ivory. They exported ambergris, gold, leopard skins, slaves, and tortoise shell. They imported pottery and glassware from Asia. They also manufactured items such as cotton, glass and shell beads. Imports and locally manufactured goods were used as trade to acquire African goods. Trade links included the Arabian Peninsula, Persia, India, and China. The Swahili also minted silver and copper coins.

Current scientific research in Africa

Ahmed Zewail, won the 1999 Nobel Prize in chemistry for his work in femtochemistry, methods that allow the description of change states in femtoseconds or very short seconds.

The Democratic Republic of the Congo has a rocketry program called Troposphere.

Currently, forty percent of African-born scientists live in OCED countries, predominantly NATO and EU countries. This has been described as an African brain drain.

Sub-Saharan African countries spent on average 0.3% of their GDP on S&T (Science and Technology) in 2007. This represents a combined increase from US$1.8bn in 2002 to US$2.8bn in 2007. North African countries spend a comparative 0.4% of GDP on research, an increase from US$2.6bn in 2002 to US$3.3bn in 2007. Exempting South Africa, the continent has augmented its collective science funding by about 50% in the last decade. Notably outstripping its neighbor states, South Africa spends 0.87% of GDP on science and technology research. Although technology parks have a long history in the US and Europe, their presence across Africa is still limited, as the continent currently lags behind other regions of the world in terms of funding technological development and innovation. Only seven countries (Morocco, Botswana, Egypt, Senegal, Madagascar, Tunisia and South Africa) have made technology park construction an integral piece of their development goals.

Africa in Science (AiS)

Africa in Science (AiS) is an online data aggregator site and ThinkTank founded in January 2021 by Aymen Idris, who currently serves as chairman. The focus of AiS ThinkTank is on scientometric analysis of science in Africa, and the main aim of the website is to monitor and display metrics such as AiS Index (AiSi) and AiS Badgethat estimate and visualize the research output of research Institutes and universities in a specific country in Africa, and their web site.

Science and technology by African region

North Africa

- Science and technology in Algeria
- Science and technology in Morocco

West Africa

- Science and technology in Cabo Verde

Central Africa

East Africa

- Science and technology in Malawi
- Science and technology in Tanzania
- Science and technology in Uganda
- Science and technology in Zimbabwe

Southern Africa

- Science and technology in Botswana
- Science and technology in South Africa