LIVES IN PREHISTORY

John Scales Avery

April 26, 2022

INTRODUCTION[1]

Human history as cultural history

We need to reform our teaching of history so that the emphasis will be placed on the gradual growth of human culture and knowledge, a growth to which all nations and ethnic groups have contributed.

This book is part of a series on cultural history. Here is a list of the other books in the series that have, until now, been completed:

- Lives in the Ancient World
- Lives in the Middle Ages
- Lives in the Renaissance
- Lives in the 17th Century
- Lives in the 18th Century
- Lives in the 19th Century
- Lives in the 20th century
- Lives in Biology
- Lives of Some Great Novelists
- Lives in Mathematics
- Lives in Exploration
- Lives in Education
- Lives in Poetry
- Lives in Painting
- Lives in Engineering
- Lives in Astronomy
- Lives in Chemistry
- Lives in Medicine
- Lives in Ecology
- Lives in Physics
- Lives in Economics
- Lives in the Peace Movement

[1] This book makes use of my previously-published book chapters, but much of the material is new.

The pdf files of these books may be downloaded and circulated free of charge from the following web addresses:

https://www.johnavery.info/

http://eacpe.org/about-john-scales-avery/

https://www.meer.com/en/authors/716-john-scales-avery

Contents

Chapter 1

OUR ANCESTORS

1.1 Timeline for the evolution of life on the Earth

The dates shown here are taken from the Wikipedia article entitled *Timeline of the evolutionary history of life*. The unit BYA means "Billion years ago", while MYA means "Million years ago".

- **4.540 BYA. Earliest Earth**
- **4.404 BYA, First appearance of water on Earth.**
- **4.280 BYA. Earliest appearance of life on Earth.**[1]
- **3.900 BYA, Cells resembling prokaryotes appear. These first organisms use CO_2 as a source of carbon, and obtain energy by oxidizing inorganic materials.**
- **3.500 BYA, Lifetime of the last universal common ancestor. The split between bacteria and archae occurs.**
- **3.000 BYA, Photosynthetic cyanobacteria evolved. They used water as a reducing agent and produced oxygen as a waste product.**
- **2.800 BYA, Earliest evidence of microbial life on land.**
- **2.500 BYA, Great Oxygenation Event, produced by cyanobacteria's oxogenic photosynthesis.**
- **1.850 BYA, Eukaryotic cells appear. They probably evolved from cooperative assemblages of prokaryotes (phagocytosis and symbiosis).**
- **1.200 BYA, Sexual reproduction first appears in the fossil records. It may have existed earlier.**
- **0.800 BYA, First multicellular organisms.**
- **0.600 BYA, The ozone layer is formed, making landbased life more possible.**
- **0.580-0.500 BYA, The Cambrian Explosion. Biodiversity quickly increases and most modern phyla of animals appear in the fossil record.**

[1] This date for the first appearance of life on earth is earlier than previously thought possible. It is based on the ratio of carbon isotopes in zircon rocks recently found in Australia.

- **0.560 BYA, Fungi appear.**
- **0.550 BYA, Comb jellies, sponges, sea anemones and corals evolved.**
- **0.530 BYA, The first known fossilized footprints on land.**
- **0.485 BYA, Jawless fishes.**
- **0.434 BYA, The first primitive plants move onto land, accompanied by fungi which may have helped them.**
- **0.420 BYA, Ray-finned fishes, arachnids, and land scorpions.**
- **0.410 BYA, First signs of teeth in fish.**
- **0.395 BYA, First lichens, stonewarts, harvestmen and springtails. The first known tracks of four-legged animals on land.**
- **0.363 BYA, The Carboniferous Period starts. Insects appear on land and soon learn to fly. Seed-bearing plants and forests cover the land.**
- **0.360 BYA, First crabs and ferns. Land flora dominated by ferns.**
- **0.350 BYA, Large sharks, ratfishes and hagfish.**
- **0.320 BYA, The precursors of mammals separate from the precursors to reptiles.**
- **0.280 BYA, Earliest beetles, seed plants and conifers diversify.**
- **0.2514 BYA, The Permian-Triassic extinction event eliminates 90-95% of marine species, and 70% of terrestrial vertebrates.[2]**
- **0.245 BYA, Earliest icthyosaurs (i.e. seagoing dinosaurs).**
- **0.225 BYA, Earliest dinosaurs. First mammals.**
- **0.220 BYA, Seed-producing forests dominate the land. Herbivours grow to huge sizes. First flies and turtles.**
- **0.155 BYA, First bloodsucking insects. Archaeopteryx, a possible ancestor of birds, appears.**
- **0.130 BYA, Rise of the flowering plants. Coevolution of plants and their pollinators.**
- **0.115 BYA, First monotreme (egg-laying) mammals.**
- **0.110 BYA, Toothed diving birds.**
- **0.100 BYA, Earliest bees.**
- **0.090 BYA, Probable origin of placental mammals. However, the first undisputed fossil evidence is from 0.066 BYA.**
- **0.080 BYA, First ants.**
- **0.066 BYA, The Cretaceous-Paleogene extinction event wipes out about half of all animal species, including all of the dinosaurs except the birds. Afterwards, mammals become the dominant animal species. Conifers dominate northern forests.**
- **0.060 BYA, Earliest true primates. Diversification of large, flightless birds. The ancestors of carnivorous mammals had appeared.**
- **0.055 BYA, Diversification of birds. First songbirds, parrots, loons, swifts, and woodpeckers. First whale.**

---

[2]Today, there is a danger that human use of fossil fuels will initiate a very similar extinction event. This danger will be discussed in a later chapter.

- **0.052 BYA, First bats appear in the fossil record.**
- **0.050 BYA, Tapirs, rhinoceroses and camels appear. Diversification of primates.**
- **0.040 BYA, Modern-type moths and butterflies were alive.**
- **0.035 BYA, Grasses diversify. Many modern mammal groups appear.**
- **0.030 BYA, Earliest pigs and cats.**
- **0.025 BYA, First deer.**
- **0.020 BYA, Giraffes, hyenas, bears, and giant anteaters appear. Birds increase in diversity.**
- **0.015 BYA, First mastodons. Australian megafauna diversify. Kangaroos appear.**
- **0.010 BYA, Grasslands and savannahs are established. Major diversification of grassland animals and snakes. Insects diversify, especially ants and termites.**
- **0.0095 BYA = 9.50 MYA, Great American Interchange occurs. Armadillos, opossums, hummingbirds, "terror birds", and ground sloths were among the species that migrated from South America to North America after a land bridge formed between the previously isolated continents. Species moving in the opposite direction included horses, tapirs, saber-toothed cats, jaguars, bears, coaties, ferrets, otters, skunks and deer.**

- **6.50 MYA, First homanins (our human ancestors diverging from the apes).**

- **6.00 MYA, Australopithecines (extinct close relatives of humans after the split with chimpanzees) diversify.**
- **5.00 MYA, First tree sloths and hippopotami. Diversification of grazing and carnivorous mammals.**
- **4.00 MYA, Diversification of Australopithecines. The first modern elephants, giraffes, zebras, lions, rhinoceros and gazelles.**
- **2.80 MYA, Appearance of a species intermediate between the Anthropithecines and Homo Habilis.**
- **2.10 MYA, First member of the genus *Homo* appears, Homo habilis.**

1.2 Early ancestors of humans

In his *Systema Naturae*, published in 1735, Carolus Linnaeus correctly classified humans as mammals associated with the anthropoid apes. However, illustrations of possible ancestors of humans in a later book by Linnaeus, showed one with a manlike head on top of a long-haired body, and another with a tail. A century later, in 1856, light was thrown on human ancestry by the discovery of some remarkable bones in a limestone cave in the valley of Neander, near Düsseldorf - a skullcap and some associated long bones. The skullcap was clearly manlike, but the forehead was low and thick, with massive ridges over the eyes. The famous pathologist Rudolf Virchow dismissed the find as a relatively recent pathological idiot. Other authorities thought that it was "one of the Cossacks who came from Russia in 1814". Darwin knew of the "Neanderthal man", but he was too ill to travel to Germany and examine the bones. However, Thomas Huxley examined them, and in his 1873 book, Zoological Evidences of Man's Place in Nature, he wrote: "Under whatever aspect we view this cranium... we meet with apelike characteristics, stamping it as the most pithecoid (apelike) of human crania yet discovered."

"In some older strata," Huxley continued, "do the fossilized bones of an ape more anthropoid, or a man more pithecoid, than any yet known await the researches of some unborn paleontologist?" Huxley's question obsessed Eugène Dubois, a young Dutch physician, who reasoned that such a find would be most likely in Africa, the home of chimpanzees and gorillas, or in the East Indies, where orang-outangs live. He was therefore happy to be appointed to a post in Sumatra in 1887. While there, Dubois heard of a site in Java where the local people had discovered many ancient fossil bones, and at this site, after much searching, he uncovered a cranium which was much too low and flat to have belonged to a modern human. On the other hand it had features which proved that it could not have belonged to an ape. Near the cranium, Dubois found a leg bone which clearly indicated upright locomotion, and which he (mistakenly) believed to belong to the same creature. In announcing his find in 1894, Dubois proposed the provocative name "Pithecanthropus erectus", i.e. "upright-walking ape-man"

Instead of being praised for this discovery, Dubois was denounced. His attackers included not only the clergy, but also many scientists (who had expected that an early ancestor of man would have an enlarged brain associated with an apelike body, rather than apelike head associated with upright locomotion). He patiently exhibited the fossil bones at scientific meetings throughout Europe, and gave full accounts of the details of the site where he had unearthed them. When the attacks nevertheless continued, Dubois became disheartened, and locked the fossils in a strongbox, out of public view, for the next 28 years. In 1923, however, he released a cast of the skull, which showed that the brain volume was about 900 cm^3 - well above the range of apes, but below the 1200-1600 cm^3 range which characterizes modern man. Thereafter he again began to exhibit the bones at scientific meetings.

The fossil bones of about 1000 hominids, intermediate between apes and humans, have now been discovered. The oldest remains have been found in Africa. Many of these were discovered by Raymond Dart and Robert Broom, who worked in South Africa, and by Louis and Mary Leakey and their son Richard, who made their discoveries at the Olduvai Gorge in Tanzania and at Lake Rudolph in Kenya.

One can deduce from biochemical evidence that the most recent common ancestor of the anthropoid apes and of humans lived in Africa between 5 and 10 million years before the present. Although the community of palaeoanthropologists is by no means unanimous, there is reasonably general agreement that while A. africanus is probably an ancestor of H. habilis and of humans, the "robust" species, A. aethiopicus, A. robustus and A. boisei1[3]

[3] A. boisei was originally called "Zinjanthropus boisei" by Mary and Louis Leakey who discovered the

represent a sidebranch which finally died out. “Pithecanthropus erectus”, found by Dubois, is now classified as a variety of Homo erectus, as is “Sinanthropus pekinensis” (”Peking man”), discovered in 1929 near Beijing, China.

Footprints 3.7 million years old showing upright locomotion have been discovered near Laetoli in Tanzania. The Laetoli footprints are believed to have been made by A. afarensis, which was definitely bipedal, but upright locomotion is thought to have started much earlier. There is even indirect evidence which suggests that A. ramidus may have been bipedal. Homo habilis was discovered by Mary and Louis Leakey at the Olduvai Gorge, among beds of extremely numerous pebble tools. The Leakeys gave this name (meaning “handy man”) to their discovery in order to call special attention to his use of tools. The brain of H. habilis is more human than that of A. africanus, and in particular, the bulge of Broca’s area, essential for speech, can be seen on one of the skull casts. This makes it seem likely that H. habilis was capable of at least rudimentary speech.

Homo erectus was the first species of hominid to leave Africa, and his remains are found not only there, but also in Europe and Asia. “Peking man”, who belonged to this species, probably used fire. The stone tools of H. erectus were more advanced than those of H. habilis; and there is no sharp line of demarcation between the most evolved examples of H. erectus and early fossils of archaic H. sapiens.

Homo sapiens neanderthalensis lived side by side with Homo sapiens sapiens (modern man) for a hundred thousand years; but in relatively recent times, only 30,000 years ago, Neanderthal man disappeared. Did modern man outcompete him? Do present-day humans carry any Neanderthal genes? To what extent was modern man influenced by Neanderthal cultural achievements? Future research may tell us the answers to these questions, but for the moment they are mysteries.

The hominid species shown in Table 4.1 show an overall progression in various characteristics: Their body size and brain size grew. They began to mature more slowly and to live longer. Their tools and weapons increased in sophistication. Meanwhile their teeth became smaller, and their skeletons more gracile - less heavy in proportion to their size. What were the evolutionary forces which produced these changes? How were they rewarded by a better chance of survival?

---

fossil remains at the Olduvai Gorge. Charles Boise helped to finance the Leakey’s expedition.

Table 1.1: **Hominid species**

genus and species	years before present	brain volume
Ardipithicus ramidus	4.35 to 4.45 million	300 to 350 cm^2
Australopithecus anamensis	4.2 to 3.9 million	
Australopithecus afarensis	3.9 to 3.0 million	375 to 550 cm^3
Australopithecus africanus	3 to 2 million	420 to 500 cm^3
Australopithecus aethiopicus	2.6 to 2.3 million	410 cm^3
Paranthropus robustus	2 to 1.5 million	410 to 530 cm^3
Australopithecus boisei	2.1 to 1.1 million	530 cm^3
Homo habilis	2.1 to 1.5 million	550 to 687 cm^3
Homo erectus	1.9 to 0.143 million	750 to 1225 cm^3
Homo sapiens (archaic)	0.5 to 0.2 million	1200 cm^3
Homo sapiens neand.	0.23 to 0.04 million	1450 cm^3
Homo sapiens sapiens	0.12 mil. to present	1350 cm^3

Table 1.2: **Paleolithic cultures**

name	years before present	characteristics
Oldowan	2.4 to 1.5 million	Africa, flaked pebble tools
Choukoutien	1.2 to 0.5 million	chopper tool culture of east Asia
Abbevillian	500,000 to 450,000	crude stone handaxes
		Africa, Europe, northeast Asia
Mousterian	70,000 to 20,000	produced by Neanderthal man,
		retouched core and flake tools,
		wooden spears, fire, burial of dead
Aurignacian	50,000 to 20,000	western Europe, fine stone blades,
		pins and awls of bone, fire, cave art
Solutrian	20,000 to 17,000	France and central Europe,
		long, pressure-flaked bifacial blades
Magdalenian	17,000 to 10,000	western Europe, reindeer hunting
		awls and needles of bone and antler

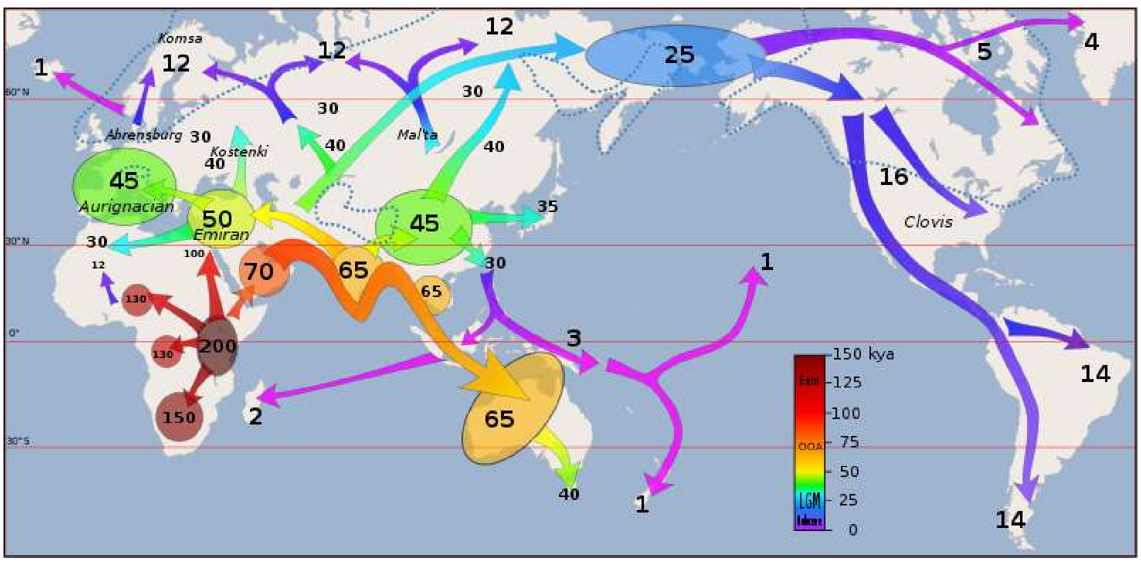


Figure 1.1: **A map showing early migrations, and the number of years, in thousands, before the present, when humans arrived at various places.**

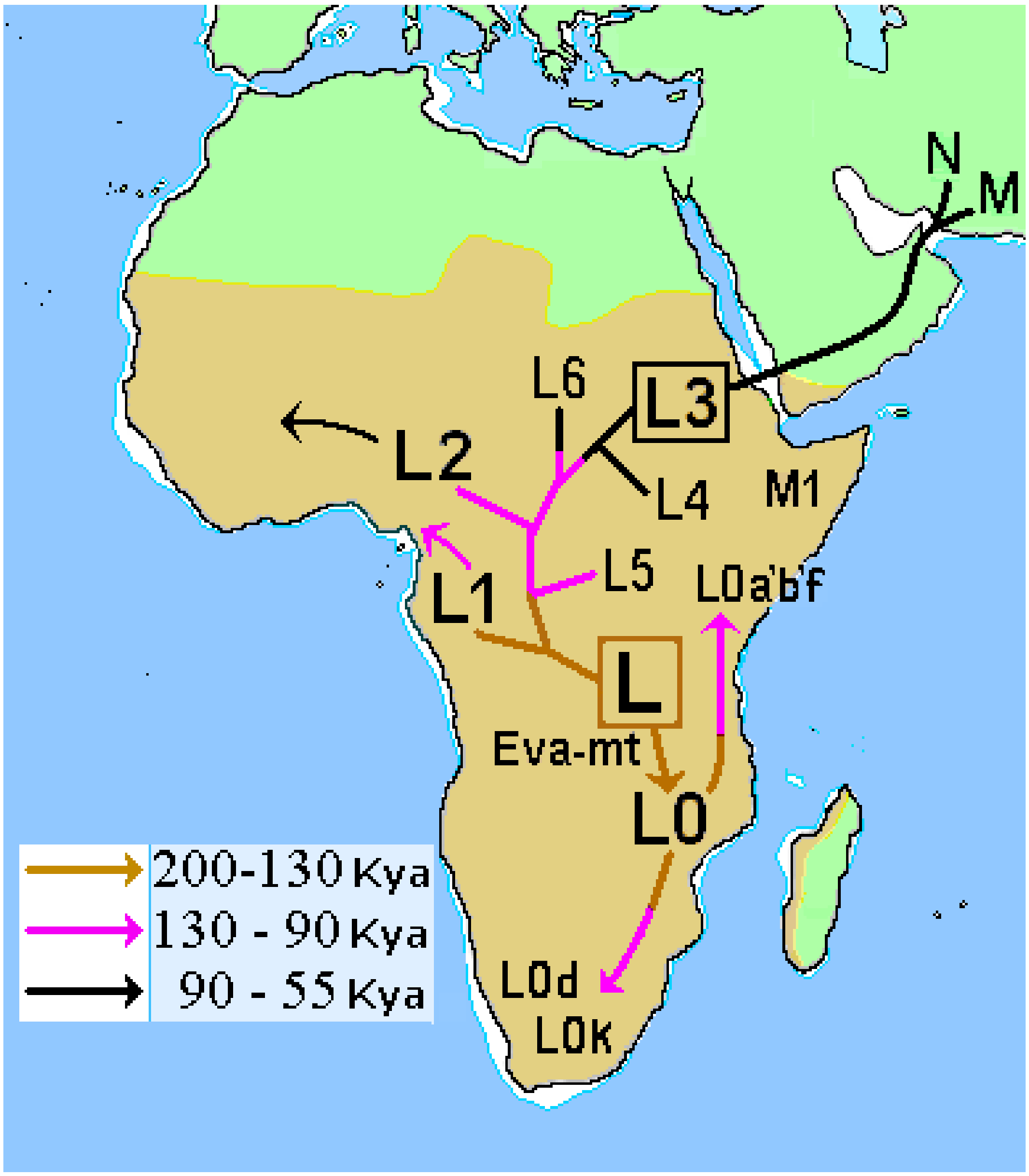


Figure 1.2: **Map of early diversification of modern humans according to mitochondrial population genetics.**

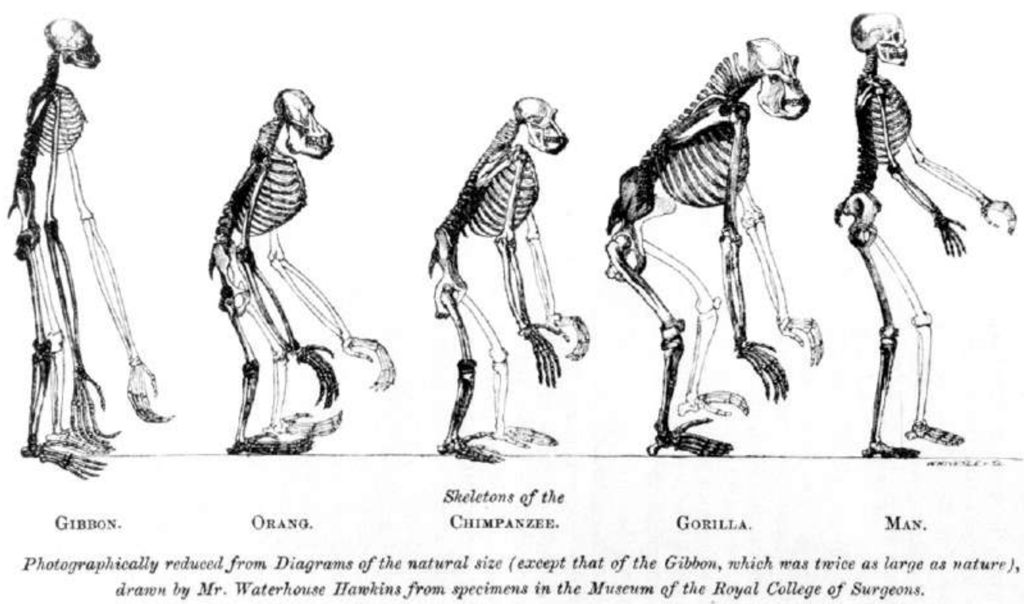


Figure 1.3: **The frontispiece to T.H. Huxley's *Evidence as to Man's Place in Nature* (1863): the image compares the skeleton of a human to other apes.**

1.3 Ardipithicus ramidus

17 bone fragments belonging to our distant ancestor, A. ramidus, were discovered in 1992-1993 by a research team headed by Tim White. The discovery was made in the Afar Depression of the Middle Awash river valley of Ethiopia. In 1994, more fragments were discovered, amounting finally to 45% of a complete skeleton. On the basis of the age of the stratum in which the bones were found, A. ramidus is thought to have lived between 4.35 and 4.45 years ago. This hominid walked upright, but had foot with a thumblike big toe which could grasp tree branches. A. ramidus had a small brain, only 300-350 cm.^{3}, which is smaller than a modern female chimpanzee. Nevertheless, the upright locomotion of the species identifies it as a human ancestor rather than an ape.

1.4 Australopithecus

Australopithecus afarensis ("Lucy")

Several hundred fossil bone fragments belonging to A. afarensis were discovered in 1974 in the Awash valley of Ethiopia, not far from the site where A. ramidus was discovered in 1992-1994. Although discovered earlier, the bones belong to one of our ancestors who lived at a later period, 3.2 million years before the present. The bones belong to a young female who was given the fanciful nickname "Lucy", after the popular Beetles song "Lucy in the Sky With Diamonds" which was being played loudly and repeatedly at the campsite of the discoverers[4].

Lucy was 1.1 meters tall, (3 feet and 7 inches), with a brain-size comparable to a modern chimpanzee, but her upright locomotion marked her as a human ancestor rather than an ape. She had long arms in relation to the length of her legs, although not so long as those of a chimpanzee.

Homo habilis ("handy man")

Louis Leakey (father of Richard Leakey), and his wife, Mary Leakey, found the first trace of H. habilis in 1955: two hominin teeth. These were later classified as "milk teeth", and therefore considered difficult to link to taxa, unlike permanent teeth. However, in 1959, Mary Leakey recovered the cranium of a young adult that had a small brain, large face, tiny canines and massive chewing teeth. The remains were associated with stone tools of the Oldowan type. In 1964 the fossils were identified as a separate species and given the name Homo habilis.

Short in stature, with disproportionately long arms compared with H. sapiens, and a brain about half the size of that of modern humans, H. habilis was very apelike, and many palaeoanthropologists believe that the species ought to be classified with the Australop-

[4]Donald Johanson, Mary Leakey, Yves Coppens and their team.

Figure 1.4: **"Lucy" skeleton, Australopithecus afarensis, cast from Museum national d'histoire naturelle, Paris.**

Figure 1.5: **Side view of cast of Lucy in the Naturmuseum Senckenberg.**

ithicenes. On the other hand, the relatively advances stone tools and omnivorous diet of H. habilis support the classification of the species within the genus Homo.

Homo erectus

As mentioned above, the first fossil remains of H. erectus were discovered in Sumatra in 1857 by the young Dutch physician, Eugène Dubois. Most palaeoanthropologists believe that H. erectus evolved in Africa, and was the first hominin to leave that continent, during a period when the climates of Africa and the Middle East were more favorable to migration then they later became. However, there is a minority school of thought that maintains that H. erectus evolved in Asia. In any case the species survived in Asia until only 143,000 years before the present, and was able to use fire.

Homo neanderthalensis

The species H. neandrithalensis ("Neanderthal Man") takes its name from the mountain valley near to Düsseldorf where fossil remains were discovered in 1856.[5] The presence in the Middle East of this successful and physically powerful species is probably the reason why the first attempts of H. sapiens to leave Africa failed.

The Wikipedia article on Homo heidelbergensis states that "Neanderthals, Denisovans, and modern humans are all considered to have descended from Homo heidelbergensis that appeared around 700,000 years ago in Africa. Fossils have been recovered in Ethiopia, Namibia and South Africa. Between 400,000 and 300,000 years ago a group of Homo heidelbergensis migrated into Europe and West Asia via yet unknown routes and eventually evolved into Neanderthals."

Denisovans are eastern cousin of the Neanderthals, and the genes of both species have been sequenced by Prof. Svante Pääbo and his colleagues at the Max Planck Institute for Evolutionary Anthropology. The results of these studies show that the genomes of modern humans outside of Africa contain an appreciable amount of genetic information derived from interbreeding with Neanderthals and Denisovans.

[5] Earlier fossils of H. neanderthalensis were discovered in Belgium in 1829, and in Gibraltar in 1848, but the importance of these discoveries was not recognized.

Figure 1.6: **Australopithecus afarensis. One famous member of this species, nicknames "Lucy", was 1.1 meters tall and lived 3.2 million years ago.**

Figure 1.7: **Australopithecus afarensis: a hunting scene. Males of the species are seen here using weapons and cooperative tactics.**

Figure 1.8: **Homo habilis, "handy man", was very apelike in size and appearance, but used a more advanced toolkit than previous hominins.**

Figure 1.9: **Homo habilis is seen here making and using tools.**

Figure 1.10: **Homo erectus left Africa, and spread throughout Eurasia, as far as Georgia, Armenia, India, Sri Lanka, China and Indonesia.**

Figure 1.11: **Homo erectus using fire.**

1.5 Y-chromosomal DNA and mitochondrial DNA

Recent DNA studies have cast much light on human prehistory, and especially on the story of how a small group of anatomically and behaviorally modern humans left Africa and populated the remainder of the world. Two types of DNA have been especially useful - Y-chromosomal DNA and mitochondrial DNA.

When we reproduce, the man's sperm carries either an X chromosome or a Y chromosome. It is almost equally probable which of the two it carries. The waiting egg of the mother has an X chromosome with complete certainty. When the sperm and egg unite to form a fertilized egg and later an embryo, the YX combinations become boys while the XX combinations become girls. Thus every male human carries a Y chromosome inherited from his father, and in fact this chromosome exists in every cell of a male's body.

Humans have a total of 23 chromosomes, and most of these participate in what might be called the "genetic lottery" - part of the remaining 22 chromosomes come from the father, and part from the mother, and it is a matter of chance which parent contributes which chromosome. Because of this genetic lottery, no two humans are genetically the same, except in the case of identical twins. This diversity is a great advantage, not only because it provides natural selection variation on which to act, but also it because prevents parasites from mimicking our cell-surface antigens and thus outwitting our immune systems. In fact the two advantages of diversity just mentioned are so great that sexual reproduction is almost universal among higher animals and plants.

Because of its special role in determining the sex of offspring, the Y chromosome is exempted from participation in the genetic lottery. This makes it an especially interesting object of study because the only changes that occur in Y chromosomes as they are handed down between generations are mutations. These mutations are not only infrequent but they also happen at a calculable rate. Thus by studying Y-chromosomal lineages, researchers have been able not only to build up prehistoric family trees but also to assign dates to events associated with the lineages.

The mutation M168 seems to have occurred just before the ancestral population of anatomically and behaviorally modern humans left Africa, roughly 60,000 years ago. All of the men who left Africa at that time carried this mutation. The descendents of this small group, probably a single tribe, were destined to populate the entire world outside Africa.

After M168, further mutations occurred, giving rise to the Y-chromosomal groups C, D, E and F-R. Men carrying Y chromosomes of type C migrated to Central Asia, East Asia and Australia/New Guinea. The D group settled in Central Asia, while men carrying Y chromosomes of type E can be found today in East Asia, Sub-Saharan Africa, the Middle East, West Eurasia, and Central Asia. Populations carrying Y chromosomes of types F-R migrated to all parts of the world outside Africa. Those members of population P who found their way to the Americas carried the mutation M242. Only indigenous men of the Americas have Y chromosomes with M242.

Mitochondrial DNA is present in the bodies of both men and women, but is handed on only from mother to daughter. The human family tree constructed from mutations in mitochondrial DNA is closely parallel to the tree constructed by studying Y chromosomes. In both trees we see that only a single small group left Africa, and that the descendents of this small group populated the remainder of the world. The mitochondrial groups L1a, L1b, and L2 are confined to Sub-Saharan Africa, but by following the lineage L3 we see a path leading out of Africa towards the population of the remainder of the world, as is shown in the next figure.

While the unmutated L3 lineage remained in Africa, a slightly changed group of people found their way out. It seems to have been a surprisingly small group, perhaps only a single tribe. Their descendents populated the remainder of the the world. The branching between the N and M lineages occurred after their exodus from Africa. All women in Western Eurasia are daughters of the N line, while in Eastern Eurasia women are descended from both the N and M lineages. Daughters of both N and M reached the Americas.

Mitochondrial DNA is also exempted from participation in the genetic lottery, but for a different reason. Mitochondria were once free-living eubacteria of a type called alpha-proteobacteria. These free-living bacteria were able perform oxidative phosphorylation, i.e. they could couple the combustion of glucose to the formation of the high-energy phosphate bond in ATP. When photosynthesis evolved, the earth's atmosphere became rich in oxygen, which was a deadly poison to most of the organisms alive at the time. Two billion years ago, when atmospheric oxygen began to increase in earnest, many organisms retreated into anaerobic ecological niches, while others became extinct; but some survived the oxygen crisis by incorporating alpha-proteobacteria into their cells and living with them symbiotically. Today, mitochondria living as endosymbionts in all animal cells, use oxygen constructively to couple the burning of food with the synthesis of ATP. As a relic of the time when they were free-living bacteria, mitochondria have their own DNA, which contained within them rather than within the cell nuclei.

When a sperm and an egg combine, the sperm's mitochondria are lost; and therefore all of the mitochondria in the body of a human child come from his or her mother. Just as Y-chromosomal DNA is passed essentially unchanged between generations in the male lines of a family tree, mitochondrial DNA is passed on almost without change in the female lines. The only changes in both cases are small and infrequent mutations. By estimating the frequency of these mutations, researchers can assign approximate dates to events in human prehistory.

On the female side of the human family tree, all lines lead back to a single woman, whom we might call "Mitochondrial Eve". Similarly, all the lines of the male family tree lead back to a single man, to whom we can give the name "Y-Chromosomal Adam". ("Eve" and "Adam" were not married, however; they were not even contemporaries!)

But why do the female and male and family trees both lead back to single individuals? This has to do with a phenomenon called "genetic drift". Sometimes a man will have no sons, and in that case, his male line will end, thus reducing the total number of Y-chromosomes in the population. Finally, after many generations, all Y-chromosomes will have dropped away through the ending of male lines except those that can be traced back to a single individual. Similar considerations hold for female lines.

When did Y-Chromosomal Adam walk the earth? Peter Underhill and his colleagues

Table 1.3: **Events leading up to the dispersal of fully modern humans from Africa (a model proposed by Sir Paul Mellars).**

Years before present	Event
150,000-200,000 BP	Initial emergence of anatomically modern populations in Africa
110,000-90,000 BP	Temporary dispersal of anatomically modern populations (with Middle Paleolithic technology) from Africa to southwest Asia, associated with clear symbolic expression
80,000-70,000 BP	Rapid climatic and environmental changes in Africa
80,000-70,000 BP	Major technological, economic and social changes in south and east Africa
70,000-60,000 BP	Major population expansion in Africa from small source area
ca. 60,000 BP	Dispersal of modern populations from Africa to Eurasia

at Stanford University calculate that, on the basis of DNA evidence, Adam lived between 40,000 and 140,000 years before the present (BP). However, on the basis of other evidence (for example the dating of archaeological sites in Australia) 40,000 years BP can be ruled out as being much too recent. Similar calculations on the date of Mitochondrial Eve find that she lived very approximately 150,000 years BP, but again there is a wide error range.

Figure 1.12: **Homo neandrithalensis. In 1997, Prof. Dr. Svante Pääbo and his colleagues at the Max Planck Institute for Evolutionary Anthropology reported their successful sequencing of Neanderthal mitochondrial DNA. Later they sequenced the DNA of Denisovans, the eastern cousins of the Neanderthals. They were also able to show that 3-5% of the DNA of humans living outside Africa is shared with Neanderthals and Denisovans, indicating intermarriage, or at least interbreeding.**

Figure 1.13: **Homo neandrithalensis working happily in front of his dwelling. The brain size of Neanderthals was larger than that of modern humans, but their linguistic abilities may have been inferior to those of H. sapiens sapiens. The Neanderthals survived in Spain until 40,000 years ago. They are, in a sense, alive today, since their genes have been mixed with those of modern humans.**

1.6 Exodus: Out of Africa

A model for the events leading up to the exodus of fully modern humans from Africa has been proposed by Sir Paul Mellars of Cambridge University, and it is shown in Table 4.3. In the article on which this table is based, Mellars calls our attention to archaeological remains of anatomically modern humans at the sites of Skhul and Qafzeh in what is now northern Israel. The burials have been dated as having taken place 110,000-90,000 BP, and they show signs of cultural development, including ceremonial arrangement with arms folded, and sacrificial objects such as pierced shell ornaments. This early exodus was short-lived, however, probably because of competition with the long-established Neanderthal populations in the region.

In Mellars' model, rapid climatic and environmental changes took place in Africa during the period 80,000-70,000 BP. According to the Toba Catastrophe Theory[6] the climatic changes in Mellers' model were due to the eruption of a supervolcano at the site of what is now Lake Toba in Indonesia. This eruption, one of the largest known to us, took place ca. 73,000 BP, and plunged the earth into a decade of extreme cold, during which the population of our direct ancestors seem to have been reduced to a small number, perhaps

[6]The Toba Catastrophe Theory is supported by such authors as Ann Gibons, Michael R. Rampino and Steven Self

as few as 10,000 individuals[7].

The survivors of the Toba Catastrophe may have been selected for improved linguistic ability, which gave them a more advanced culture than their contemporaries. Mellers points to archaeological and genetic evidence that a major population expansion of the L2 and L3 mitochondrial lineages took place in Africa 70,000-60,000 BP, starting from a small source region in East Africa, and spreading west and south. The expanding L2 and L3 populations were characterized by advanced cultural features such as upper paleolithic technology, painting and body ornaments.

All researchers agree that it was a small group of the L3 mitochondrial lineage that made the exodus from Africa, but there is some disagreement about the date of this event. These differences reflect the intrinsic inaccuracy of the genetic dating methods, but all researchers agree that the group passing out of Africa was remarkably small, especially when we reflect that the entire population of the remainder of the world is descended from them.

The small group of modern humans leaving Africa probably crossed the Red Sea at a its narrowest point[8]. The men in this tiny but brave group of explorers carried with them the Y-chromosomal mutation M168, while the women were of the mitochondrial lineage L3. Shortly after they crossed the Red Sea (like Moses and his followers), a mutation occurred and two new mitochondrial lineages were established, M and N. All women today in Western Eurasia are daughters of the N lineage[9], while the M lineage spread to the entire world outside Africa. The mitochondrial lineages M and N had further branches, and daughters of the A, B, C, D and X lineages passed over a land bridge which linked Siberia to Alaska during the period 22,000-7,000 BP, thus reaching the Americas.

[7]Additional support to the Toba Catastrophe Theory comes from DNA studies of mammals, such as chimpanzees, orangutans, macques, cheetahs, tigers and gorillas. These mammals also seem, on the basis of DNA studies, to have been reduced to very small populations at the time of the Toba eruption.

[8]Today this narrow place is sometimes called "Gate of Grief" because many shipwrecks take place there.

[9]Of course, this broad statement does not take into account the movements of peoples that have taken place during historic times.

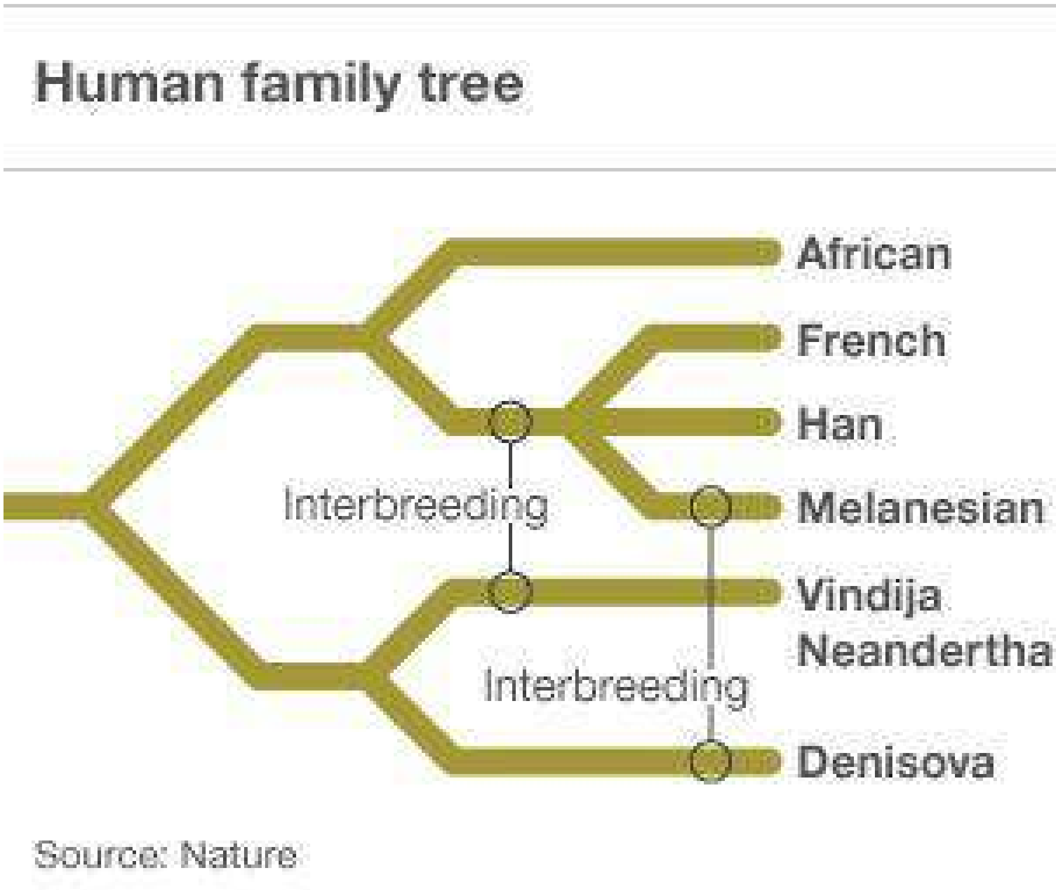


Figure 1.14: **The human family tree.**

Figure 1.15: **Domestication of the dog**

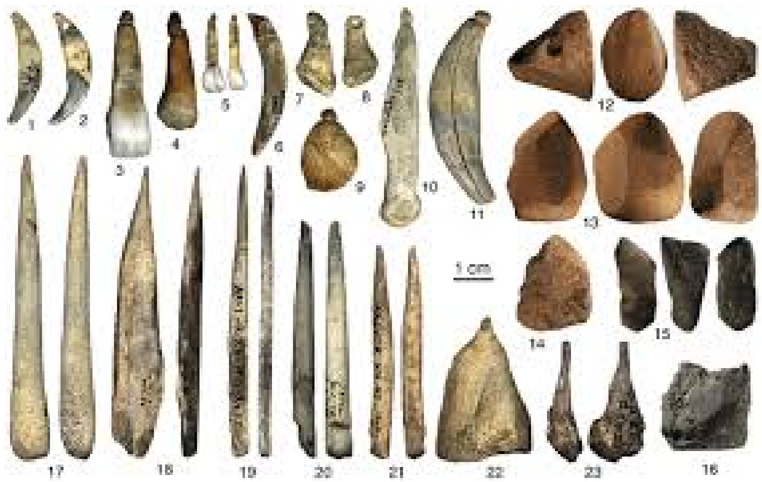


Figure 1.16: **Paleolithic stone tools**

Figure 1.17: **Neolithic stone tools were more advanced. Stone axes were highly polished and had holes to accommodate the hafts.**

Figure 1.18: **A Neolithic scene.**

1.7 Joseph Greenberg's classification of languages and DNA analysis

In his excellent and fascinating book *Before the Dawn*, the science journalist Nicholas Wade discusses linguistic studies that support the early human migration scenarios that can be deduced from DNA research. The work of the unconventional but visionary linguist Joseph Greenberg of Stanford University is particularly interesting.

While other linguists were content to demonstrate relationships between a few languages, such as those in the Indo-European family, Greenberg attempted to arrange all known languages into an enormous family tree. He published this work in the 1950's, long before the DNA studies that we have just been discussing, and because of what other linguists regarded as lack of rigor in his methods, Greenberg's prophetic voice was largely ignored by his peers. The linguist Paul Newman recalls visiting the London School of Oriental and African Studies ca. 1970. He was told that he could use the Common Room as long has he promised never to mention the name of Joseph Greenberg.

Finally, after Joseph Greenberg's death, his visionary studies were vindicated by DNA-based human migration scenarios, which agreed in surprising detail with the great but neglected scholar's linguistically-based story of how early humans left their ancestral homeland in Africa and populated the entire earth.

The Wikipedia article on Joseph Greenberg states that "Greenberg's reputation rests partly on his contributions to synchronic linguistics and the quest to identify linguistic universals. During the late 1950s, Greenberg began to examine languages covering a wide geographic and genetic distribution. He located a number of interesting potential universals as well as many strong cross-linguistic tendencies.

"In particular, Greenberg conceptualized the idea of 'implicational universal', which has the form, 'if a language has structure X, then it must also have structure Y.' For example, X might be 'mid front rounded vowels' and Y 'high front rounded vowels' (for terminology see phonetics). Many scholars adopted this kind of research following Greenberg's example and it remains important in synchronic linguistics.

Figure 1.19: A photograph of the great but controversial linguist Joseph Greenberg (1915-2001). After his death, his visionary studies were vindicated by DNA-based human migration scenarios, which agreed in surprising detail with Greenberg's linguistically-based story of how early humans left their ancestral homeland in Africa and populated the entire earth.

"Like Noam Chomsky, Greenberg sought to discover the universal structures on which human language is based. Unlike Chomsky, Greenberg's method was functionalist, rather than formalist. An argument to reconcile the Greenbergian and Chomskyan methods can be found in Linguistic Universals (2006), edited by Ricardo Mairal and Juana Gil ."

Suggestions for further reading

1. D.R. Griffin, *Animal Mind - Human Mind*, Dahlem Conferenzen 1982, Springer, Berlin, (1982).
2. S. Savage-Rumbaugh, R. Lewin, et al., Kanzi: *The Ape at the Brink of the Human Mind*, John Wiley and Sons, New York, (1996).
3. R. Dunbar, *Grooming, Gossip, and the Evolution of Language*, Harvard University Press, (1998).
4. J.H. Greenberg, *Research on language universals*, Annual Review of Anthropology, *4*, 75-94 (1975).
5. M.E. Bitterman, *The evolution of intelligence*, Scientific American, January, (1965).
6. R. Fox, *In the beginning: Aspects of hominid behavioral evolution*, Man, *NS 2*, 415-433 (1967).
7. M.S. Gazzaniga, *The split brain in man*, Scientific American, *217*, 24-29 (1967).
8. D. Kimura, *The asymmetry of the human brain*, Scientific American, **228**, 70-78 (1973).
9. R.G. Klein, *Anatomy, behavior, and modern human origins*, Journal of World Prehistory, *9 (2)*, 167-198 (1995).
10. N.G. Jablonski and L.C. Aiello, editors, *The Origin and Diversification of Language*, Wattis Symposium Series in Anthropology. Mem- oirs of the California Academy of Sciences, *No. 24*, The California Academy of Sciences, San Francisco, (1998).
11. S. Pinker, *The Language Instinct: How the Mind Creates Language*, Harper-Collins Publishers, New York, (1995).
12. S. Pinker, *Talk of genetics and visa versa*, Nature, *413*, 465-466, (2001).
13. S. Pinker, *Words and rules in the human brain*, Nature, *387*, 547-548, (1997).
14. J.H. Barkow, L. Cosmides and J. Tooby, editors, *The Adapted Mind: Evolutionary Psychology and the Generation of Culture*, Oxford University Press, (1995).
15. D.R. Begun, C.V. Ward and M.D. Rose, *Function, Phylogeny and Fossils: Miocene Hominid Evolution and Adaptations*, Plenum Press, New York, (1997).
16. R.W. Byrne and A.W. Whitten, *Machiavellian Intelligence: Social Expertise and the Evolution of Intellect in Monkeys, Apes and Humans*, Cambridge University Press, (1988),
17. V.P. Clark, P.A. Escholz and A.F. Rosa, editors, *Language: Readings in Language and Culture*, St Martin's Press, New York, (1997).
18. T.W. Deacon, *The Symbolic Species: The Co-evolution of Language and the Brain*, W.W. Norton and Company, New York, (1997).
19. C. Gamble, *Timewalkers: The Prehistory of Global Colonization*, Harvard University Press, (1994).
20. K.R. Gibson and T. Inglod, editors, *Tools, Language and Cognition in Human Evolution*, Cambridge University Press, (1993).
21. P. Mellers, *The Emergence of Modern Humans: An Archeological Per- spective*, Edinburgh University Press, (1990).
22. P. Mellers, *The Neanderthal Legacy: An Archeological Perspective of Western Europe*, Princeton University Press, (1996).

23. S. Mithen, *The Prehistory of the Mind*, Thames and Hudson, London, (1996).
24. D. Haraway, *Signs of dominance: from a physiology to a cybernetics, of primate biology*, C.R. Carpenter, 1939-1970, Studies in History of Biology, *6*, 129-219 (1983).
25. D. Johanson and M. Edey, *Lucy: The Beginnings of Humankind*, Simon and Schuster, New York, (1981).
26. B. Kurten, *Our Earliest Ancestors*, Colombia University Press, New York, (1992).
27. R. Lass, *Historical Linguistics and Language Change*, Cambridge University Press, (1997).
28. R.E. Leakey and R. Lewin, *Origins Reconsidered*, Doubleday, New York, (1992).
29. P. Lieberman, *The Biology and Evolution of Language*, Harvard University Press, (1984).
30. C.S.L. Lai, S.E. Fisher, J.A, Hurst, F. Vargha-Khadems, and A.P. Monaco, *A forkhead-domain gene is mutated in a severe speech and language disorder*, Nature, *413*, 519-523, (2001).
31. W. Enard, M. Przeworski, S.E. Fisher, C.S.L. Lai, V. Wiebe, T. Kitano, A.P. Monaco, and S. Paabo, *Molecular evolution of FOXP2, a gene involved in speech and language*, Nature AOP, published online 14 August 2002.
32. M. Gopnik and M.B. Crago, *Familial aggregation of a developmental language disorder*, Cognition, *39*, 1-50 (1991).
33. K.E. Watkins, N.F. Dronkers, and F. Vargha-Khadem, *Behavioural analysis of an inherited speech and language disorder. Comparison with acquired aphasia*, Brain, *125*, 452-464 (2002).
34. J.D. Wall and M. Przeworski, *When did the human population size start increasing?*, Genetics, *155*, 1865-1874 (2000).
35. L. Aiello and C. Dean, An *Introduction to Human Evolutionary Anatomy*, Academic Press, London, (1990).
36. F. Ikawa-Smith, ed., *Early Paleolithic in South and East Asia*, Mouton, The Hague, (1978).
37. M. Aitken, *Science Based Dating in Archeology*, Longman, London, (1990).
38. R.R. Baker, *Migration: Paths Through Space and Time*, Hodder and Stoughton, London, (1982).
39. P. Bellwood, *Prehistory of the Indo-Malaysian Archipelago*, Academic Press, Sidney, (1985).
40. P.J. Bowler, *Theories of Human Evolution: A Century of Debate*, 1884-1944, Basil Blackwell, Oxford, (1986).
41. G. Isaac and M. McCown, eds., *Human Origins: Louis Leakey and the East African Evidence*, Benjamin, Menlo Park, (1976).
42. F.J. Brown, R. Leakey, and A. Walker, *Early Homo erectus skeleton from west Lake Turkana, Kenya*, Nature, *316*, 788-92 (1985).
43. K.W. Butzer, *Archeology as Human Ecology*, Cambridge University Press, (1982).
44. A.T. Chamberlain and B.A. Wood, *Early hominid phytogeny*, Journal of Human Evolution, *16*, 119-33, (1987).

45. P. Mellars and C. Stringer, eds., *The Human Revolution: Behavioural and Biological Perspectives in the Origins of Modern Humans*, Edinburgh University Press, (1989).
46. G.C. Conroy, *Primate Evolution*, W.W. Norton, New York, (1990).
47. R.I.M. Dunbar, *Primate Social Systems*, Croom Helm, London, (1988).
48. B. Fagan, *The Great Journey: The Peopling of Ancient America*, Thames and Hudson, London, (1987).
49. R.A. Foley, ed., *Hominid Evolution and Community Ecology*, Academic Press, New York, (1984).
50. S.R. Binford and L.R. Binford, *Stone tools and human behavior*, Scientific American, *220*, 70-84, (1969).
51. G. Klein, *The Human Career, Human Biological and Cultural Origins*, University of Chicago Press, (1989).
52. B.F. Skinner and N. Chomsky, *Verbal behavior, Language*, *35*, 26-58 (1959).
53. D. Bickerton, *The Roots of Language*, Karoma, Ann Arbor, Mich., (1981).
54. E. Lenneberg in *The Structure of Language: Readings in the Philosophy of Language*, J.A. Fodor and J.A. Katz editors, Prentice-Hall, Englewood Cliffs N.J., (1964).
55. M. Ruhelen, *The Origin of Language*, Wiley, New York, (1994).
56. C.B. Stringer and R. McKie, *African Exodus: The Origins of Modern Humanity*, Johnathan Cape, London (1996).
57. R. Lee and I. DeVore, editors, *Kalahari Hunter-Gatherers*, Harvard University Press, (1975).
58. R.W. Sussman, *The Biological Basis of Human Behavior*, Prentice Hall, Englewood Cliffs, (1997).

Chapter 2

THE ORIGIN OF HUMAN LANGUAGES

2.1 The remarkable linguistic abilities of humans

Institute Professor Noam Chomsky of MIT, and more recently the University of Arizona, was born in 1928 in Philadelphia. Today he is considered to be the world's greatest public intellectual, and is famed as a linguist, philosopher, cognitive scientist, historian, social critic, and political activist. The author of more than 100 books, Prof. Chomsky has been called "the father of modern linguistics".

The Wikipedia article on Prof. Chomsky states that "From 1951 to 1955 he was appointed to Harvard University's Society of Fellows, where he developed the theory of transformational grammar for which he was awarded his doctorate in 1955. That year he began teaching at MIT, in 1957 emerging as a significant figure in the field of linguistics for his landmark work Syntactic Structures, which remodeled the scientific study of language, while from 1958 to 1959 he was a National Science Foundation fellow at the Institute for Advanced Study. He is credited as the creator or co-creator of the universal grammar theory, the generative grammar theory, the Chomsky hierarchy, and the minimalist program.

"Since the 1960s, Chomsky has maintained that syntactic knowledge is at least partially inborn, implying that children need only learn certain parochial features of their native languages. Chomsky based his argument on observations about human language acquisition, noting that there is an enormous gap between the linguistic stimuli to which children are exposed and the rich linguistic knowledge they attain (see: 'poverty of the stimulus' argument). For example, although children are exposed to only a finite subset of the allowable syntactic variants within their first language, they somehow acquire the ability to understand and produce an infinite number of sentences, including ones that have never before been uttered.

Figure 2.1: **As the famous professor of linguistics, Noam Chomsky, has pointed out, the remarkable linguistic abilities of humans so greatly exceed those of other animals that they are qualitatively different. Professor Chomsky also asserts that humans acquired these astonishing abilities in a rather short period of time. We owe it to his stature to try to find a mechanism through which this could have occurred.**

2.2 Pathfinding circuits in the brain

The 2014 Nobel Prize in Physiology or Medicine was awarded to three scientists who discovered pathfinding circuits in the brains of animals, including humans. The three laureates were John O'Keefe, May-Britt Moser, and Edvard Moser. Their histological studies of animal brains revealed networks of cells that allow animals to remember pathways in their environments.

The decision-trees that are used in pathfinding are similar to the decision-trees used in the classification of words in a language. In this chapter, we will explore the possibility that a mutation caused the duplication of the brain.circuits discovered by O'Keefe, Moser and Moser, and that one of the duplicated circuits was slightly modified and became the basis of the remarkable linguistic abilities of humans.

Figure 2.2: **The three winners of the 2014 Nobel Prize in Physiology or Medicine.**

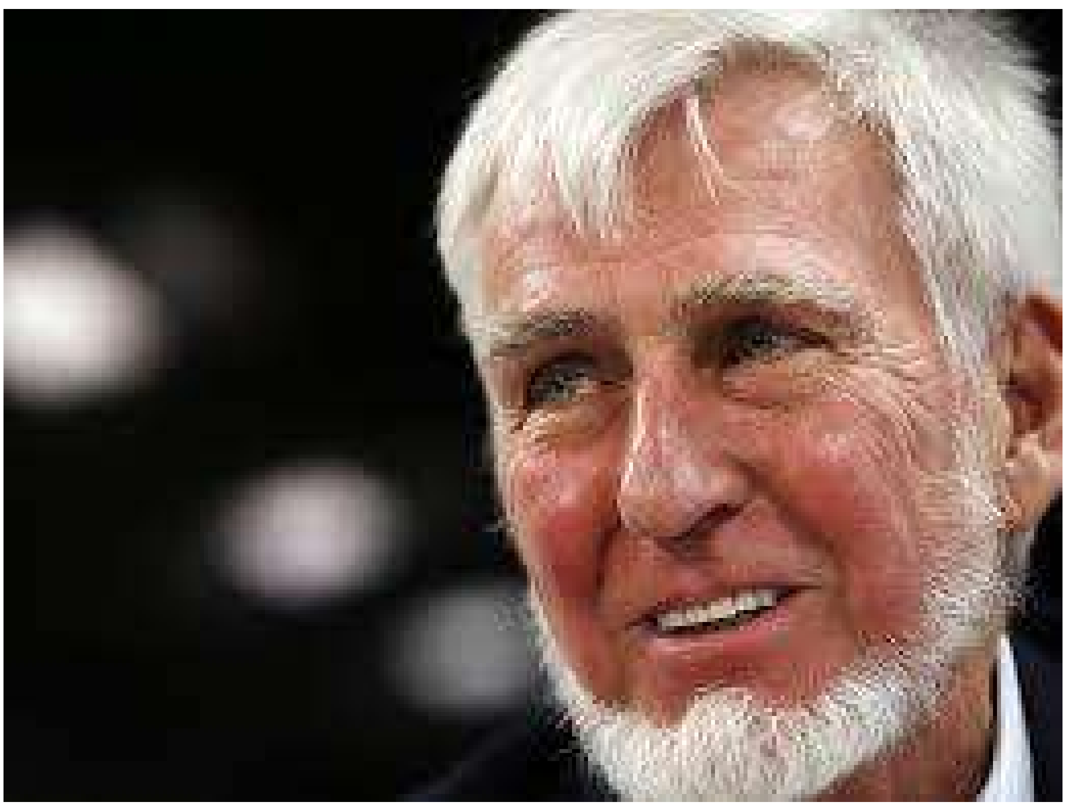


Figure 2.3: **A photo of John O'Keefe, who discovered place cells in the hippocampus. Place cells are cells that fire specifically when an animal is at a certain location in its local environment.**

2.3 Serial homologies

The fact each individual mutation affects a single gene, and hence the synthesis of a single protein, explains the gradual steps observed in evolution, first by Charles Darwin, and later by many other researchers. A mutation produces a small change in the morphology and functions of an organism, and the change is preserved if beneficial.

"serial homologies" are cases where symmetrically repeated parts of an ancient progenitor have been modified for special purposes in their descendants. For example, the bones which fit together to form the brain case in reptiles, birds and mammals can be seen in fossil sequences to be modified vertebrae of an ancient progenitor.

In his book on "The Origin of Species", after discussing many examples, Darwin exclaims, "How inexplicable are these cases of serial homologies on the ordinary view of creation! Why should the brain be enclosed in a box composed of such numerous and extraordinarily-shaped pieces of bone?... Why should similar bones have been created to form the wing and leg of a bat, used as they are for totally different purposes, namely walking and flying? Why should one crustacean, which has an extremely complex mouth, formed of many parts, consequently have fewer legs; or conversely, those with many legs have simpler mouths? Why should the sepals, petals, stamens and pistils in each flower,though fitted for such distinct purposes, be all constructed on the same pattern?... On the theory of natural selection we can, to a certain extent, answer these questions.... An indefinite repetition of the same part is the common characteristic of all low or little-specialized forms... We have already seen that parts many times repeated are eminently liable to vary... Consequently such parts, being already present in considerable numbers, and being highly variable, would naturally afford materials for adaption to the most different purposes."

2.4 A possible explanation for the origin of human linguistic abilities

There are many cases where a single mutation seems to have produced duplication of a structure. For example, we sometimes see the birth of an animal with two heads, or supernumerary legs. In the light of Professor Chomsky's observation that human languages are qualitatively different from animal languages, and his belief that modern humans acquired their astonishing linguistic abilities very rapidly, we ought to investigate the possibility that a single mutation caused a duplication of the pathfinding neural networks studied by Edvard Moser, May-Britt Moser, and John O'Keefe. We can then imagine that one copy of this duplicated pathfinding neural network system was modified to serve as the basis of human languages, in which the classification of words is closely analogous to the tree-like branching choice-pathways of an animal

finding its way through a forest or maze.[1]

Suggestions for further reading

1. Chomsky, Noam (1956). *Three models for the description of language* (PDF). IRE Transactions on Information Theory (2): 113-124. doi:10.1109/TIT.1956.1056813.
2. Michael Sipser (1997). Introduction to the Theory of Computation 1st. Cengage Learning. ISBN 0-534-94728-X. *The Church-Turing Thesis (Page 130)*
3. Chomsky, Noam (1959). *On certain formal properties of grammars* (PDF). Information and Control. 2 (2): 137-167. doi:10.1016/S0019-9958(59)90362-6.
4. Chomsky, Noam; SchÃ¼tzenberger, Marcel P. (1963). *The algebraic theory of context free languages*. In Braffort, P.; Hirschberg, D. Computer Programming and Formal Languages. Amsterdam: North Holland. pp. 118-161.
5. Green RE, Krause J, Briggs AW, et al. (May 2010). *A draft sequence of the Neandertal genome* (PDF). Science. 328 (5979): 710-722. PMID 20448178. doi:10.1126/science.1188021.
6. Zimmer, Carl (18 December 2013). *Toe Fossil Provides Complete Neanderthal Genome*. New York Times. Retrieved 18 December 2013.
7. PrÃ¼fer, Kay; et al. (18 December 2013). *The complete genome sequence of a Neanderthal from the Altai Mountains*. Nature. 505: 43-49.
8. Than, Ker (6 May 2010). *Neanderthals, Humans Interbred - First Solid DNA Evidence*. National Geographic Society. Retrieved 9 May 2010.
9. Cohen, Jon (29 June 2007). *Relative Differences: The Myth of 1%* (PDF). AAAS. *Humans and Chimps: Close But Not That Close*. Scientific American. 2006-12-19. Retrieved 2006-12-20.
10. Wong, Kate (1 September 2014). *Tiny Genetic Differences between Humans and Other Primates Pervade the Genome*. Scientific American. Retrieved 12 October 2016.
11. Gibbons, Ann (13 June 2012). *Bonobos Join Chimps as Closest Human Relatives*. Science/AAAS. *Scientists Decode Majority of Neanderthal Man's Genome*. Deutsche Welle. 13 February 2009.
12. McGroarty, Patrick (12 February 2009). *Team in Germany maps Neanderthal genome*. The Associated Press.
13. Brown, David (March 25, 2010). *DNA from bone shows new human forerunner, and raises array of questions*. Washington Post.
14. Krause J, Fu Q, Good JM, et al. (April 2010). *The complete mitochondrial DNA genome of an unknown hominin from southern Siberia*. Nature. 464 (7290): 894-897. PMID 20336068. doi:10.1038/nature08976.
15. Green, Richard E.; et al. (16 November 2006). *Analysis of one million base pairs of Neanderthal DNA* (PDF). Nature. 444 (7117): 330-336. PMID 17108958. doi:10.1038/nature05336.
16. Noonan, James P.; et al. (17 November 2006). *Sequencing and Analysis of Neanderthal Genomic DNA* (PDF). Science. 314 (5802): 1113-1118.

[1] Bold face is used here because this paragraph contains the central message of this chapter.

17. Krause J, Lalueza-Fox C, Orlando L, et al. (November 2007). *The derived FOXP2 variant of modern humans was shared with Neandertals*. Curr. Biol. 17 (21): 1908-1912. PMID 17949978. doi:10.1016/j.cub.2007.10.008.
18. Inman, Mason (12 February 2009). *Neanderthal Genome "First Draft" Unveiled.* National Geographic News.
19. Lynn Yarris (15 November 2006). *Neanderthal Genome Sequencing Yields Surprising Results and Opens a New Door to Future Studies.* Lawrence Berkeley National Laboratory. Retrieved 2009-02-16.
20. Wade, Nicholas (12 February 2009). *Scientists in Germany Draft Neanderthal Genome.* The New York Times. Retrieved 20 May 2010.
21. Wade, Nicholas (6 May 2010). *Signs of Neanderthals Mating With Humans.* The New York Times. Skull discovery suggests location where humans first had sex with Neanderthals
22. Igor V. Ovchinnikov; Anders GÃ¶therstrÃ¶m; Galina P. Romanova; Vitaliy M. Kharitonov; Kerstin LidÃ©n; William Goodwin (30 March 2000). *Molecular analysis of Neanderthal DNA from the northern Caucasus.* Letters to Nature. Nature 404. pp. 490-493. doi:10.1038/35006625. Retrieved 13 March 2011.
23. David Leveille (31 August 2012). *Scientists Map An Extinct Denisovan Girl's Genome*
24. . PRI's The World,. Retrieved 31 August 2012.
25. Brown, David (25 March 2010), *DNA from bone shows new human forerunner, and raises array of questions*, Washington Post
26. Krause, Johannes; Fu, Qiaomei; Good, Jeffrey M.; Viola, Bence; Shunkov, Michael V.; Derevianko, Anatoli P. & Pääbo, Svante (2010), *The complete mitochondrial DNA genome of an unknown hominin from southern Siberia*, Nature, 464 (7290): 894-897, PMID 20336068, doi:10.1038/nature08976
27. Zimmer, Carl (16 November 2015). *In a Tooth, DNA From Some Very Old Cousins, the Denisovans.* New York Times. Retrieved 16 November 2015.
28. Sawyer, Susanna; Renaud, Gabriel; Viola, Bence; Hublin, Jean-Jacques; Gansauge, Marie-Theres; Shunkov, Michael V.; Derevianko, Anatoly P.; Prüfer, Kay; Kelso, Janet; Pääbo, Svante (11 November 2015). *Nuclear and mitochondrial DNA sequences from two Denisovan individuals.* PNAS. Bibcode:2015PNAS..11215696S. doi:10.1073/pnas.1519905112. Retrieved 16 November 2015.
29. Davis, Martin D.; Sigal, Ron; Weyuker, Elaine J. (1994). *Computability, Complexity, and Languages: Fundamentals of Theoretical Computer Science (2nd ed.).* Boston: Academic Press, Harcourt, Brace. p. 327.
30. Rokach, Lior; Maimon, O. (2008). *Data mining with decision trees: theory and applications.* World Scientific Pub Co Inc. ISBN 978-9812771711.
31. Quinlan, J. R., (1986). *Induction of Decision Trees.* Machine Learning 1: 81-106, Kluwer Academic Publishers
32. Breiman, Leo; Friedman, J. H.; Olshen, R. A.; Stone, C. J. (1984). *Classification and regression trees.* Monterey, CA: Wadsworth & Brooks/Cole Advanced Books & Software. ISBN 978-0-412-04841-8.

33. Friedman, J. H. (1999). Stochastic gradient boosting. Stanford University. Hastie, T., Tibshirani, R., Friedman, J. H. (2001). The elements of statistical learning : Data mining, inference, and prediction. New York: Springer Verlag.
34. Breiman, L. (1996). Bagging Predictors. *Machine Learning, 24*: pp. 123-140.
35. Rodriguez, J.J. and Kuncheva, L.I. and Alonso, C.J. (2006), Rotation forest: A new classifier ensemble method, IEEE Transactions on Pattern Analysis and Machine Intelligence, 28(10):1619-1630.
36. Rivest, Ron (Nov 1987). *Learning Decision Lists* (PDF). Machine Learning. 3 (2): 229-246. doi:10.1023/A:1022607331053.
37. Letham, Ben; Rudin, Cynthia; McCormick, Tyler; Madigan, David (2015). *Interpretable Classifiers Using Rules And Bayesian Analysis: Building A Better Stroke Prediction Model*. Annals of Applied Statistics. 9: 1350-1371.
38. Wang, Fulton; Rudin, Cynthia (2015). *Falling Rule Lists* (PDF). Journal of Machine Learning Research. 38.
39. Kass, G. V. (1980). *An exploratory technique for investigating large quantities of categorical data*. Applied Statistics. 29 (2): 119-127. JSTOR 2986296. doi:10.2307/2986296.
40. Hothorn, T.; Hornik, K.; Zeileis, A. (2006). *Unbiased Recursive Partitioning: A Conditional Inference Framework*. Journal of Computational and Graphical Statistics. 15 (3): 651-674. JSTOR 27594202. doi:10.1198/106186006X133933.
41. Strobl, C.; Malley, J.; Tutz, G. (2009). *An Introduction to Recursive Partitioning: Rationale, Application and Characteristics of Classification and Regression Trees, Bagging and Random Forests*. Psychological Methods. 14 (4): 323-348. doi:10.1037/a0016973.
42. Rokach, L.; Maimon, O. (2005). *Top-down induction of decision trees classifiers-a survey*. IEEE Transactions on Systems, Man, and Cybernetics, Part C. 35 (4): 476-487. doi:10.1109/TSMCC.2004.843247.
43. Witten, Ian; Frank, Eibe; Hall, Mark (2011). Data Mining. Burlington, MA: Morgan Kaufmann. pp. 102-103. ISBN 978-0-12-374856-0.
44. Gareth, James; Witten, Daniela; Hastie, Trevor; Tibshirani, Robert (2015). An Introduction to Statistical Learning. New York: Springer. p. 315. ISBN 978-1-4614-7137-0.
45. Hyafil, Laurent; Rivest, RL (1976). *Constructing Optimal Binary Decision Trees is NP-complete*. Information Processing Letters. 5 (1): 15-17. doi:10.1016/0020-0190(76)90095-8.
46. Murthy S. (1998). Automatic construction of decision trees from data: A multidisciplinary survey. Data Mining and Knowledge Discovery
47. Ben-Gal I. Dana A., Shkolnik N. and Singer (2014). *Efficient Construction of Decision Trees by the Dual Information Distance Method* (PDF). Quality Technology & Quantitative Management (QTQM), 11(1), 133-147. *Principles of Data Mining.* 2007.
48. Horváth, Tamás; Yamamoto, Akihiro, eds. (2003). *Inductive Logic Programming.* Lecture Notes in Computer Science. 2835.

49. Deng,H.; Runger, G.; Tuv, E. (2011). Bias of importance measures for multi-valued attributes and solutions. Proceedings of the 21st International Conference on Artificial Neural Networks (ICANN). pp. 293-300. http://citeseer.ist.psu.edu/oliver93decision.html
50. Papagelis A., Kalles D.(2001). Breeding Decision Trees Using Evolutionary Techniques, Proceedings of the Eighteenth International Conference on Machine Learning, p.393-400, June 28-July 01, 2001
51. Barros, Rodrigo C., Basgalupp, M. P., Carvalho, A. C. P. L. F., Freitas, Alex A. (2011). A Survey of Evolutionary Algorithms for Decision-Tree Induction. IEEE Transactions on Systems, Man and Cybernetics, Part C: Applications and Reviews, vol. 42, n. 3, p. 291-312, May 2012.
52. Chipman, Hugh A., Edward I. George, and Robert E. McCulloch. *Bayesian CART model search.* Journal of the American Statistical Association 93.443 (1998): 935-948.
53. Barros R. C., Cerri R., Jaskowiak P. A., Carvalho, A. C. P. L. F., A bottom-up oblique decision tree induction algorithm. Proceedings of the 11th International Conference on Intelligent Systems Design and Applications (ISDA 2011).

Chapter 3

CHIMPANZEES COMPARED WITH OUR ANCESTORS

3.1 Louis Leakey's discoveries in Africa

Here are some quotations from the Wikipedia article about Louis Leakey:

"Louis Seymour Bazett Leakey (7 August 1903 - 1 October 1972) was a Kenyan-British paleoanthropologist and archaeologist whose work was important in demonstrating that humans evolved in Africa, particularly through discoveries made at Olduvai Gorge with his wife, fellow paleoanthropologist Mary Leakey. Having established a program of palaeoanthropological inquiry in eastern Africa, he also motivated many future generations to continue this scholarly work. Several members of the Leakey family became prominent scholars themselves.

"Another of Leakey's legacies stems from his role in fostering field research of primates in their natural habitats, which he saw as key to understanding human evolution. He personally focused on three female researchers, Jane Goodall, Dian Fossey, and Biruté Galdikas, calling them The Trimates. Each went on to become an important scholar in the field of primatology. Leakey also encouraged and supported many other PhD. candidates, most notably from the University of Cambridge. Leakey also played a role in creating organizations for future research in Africa and for protecting wildlife there."

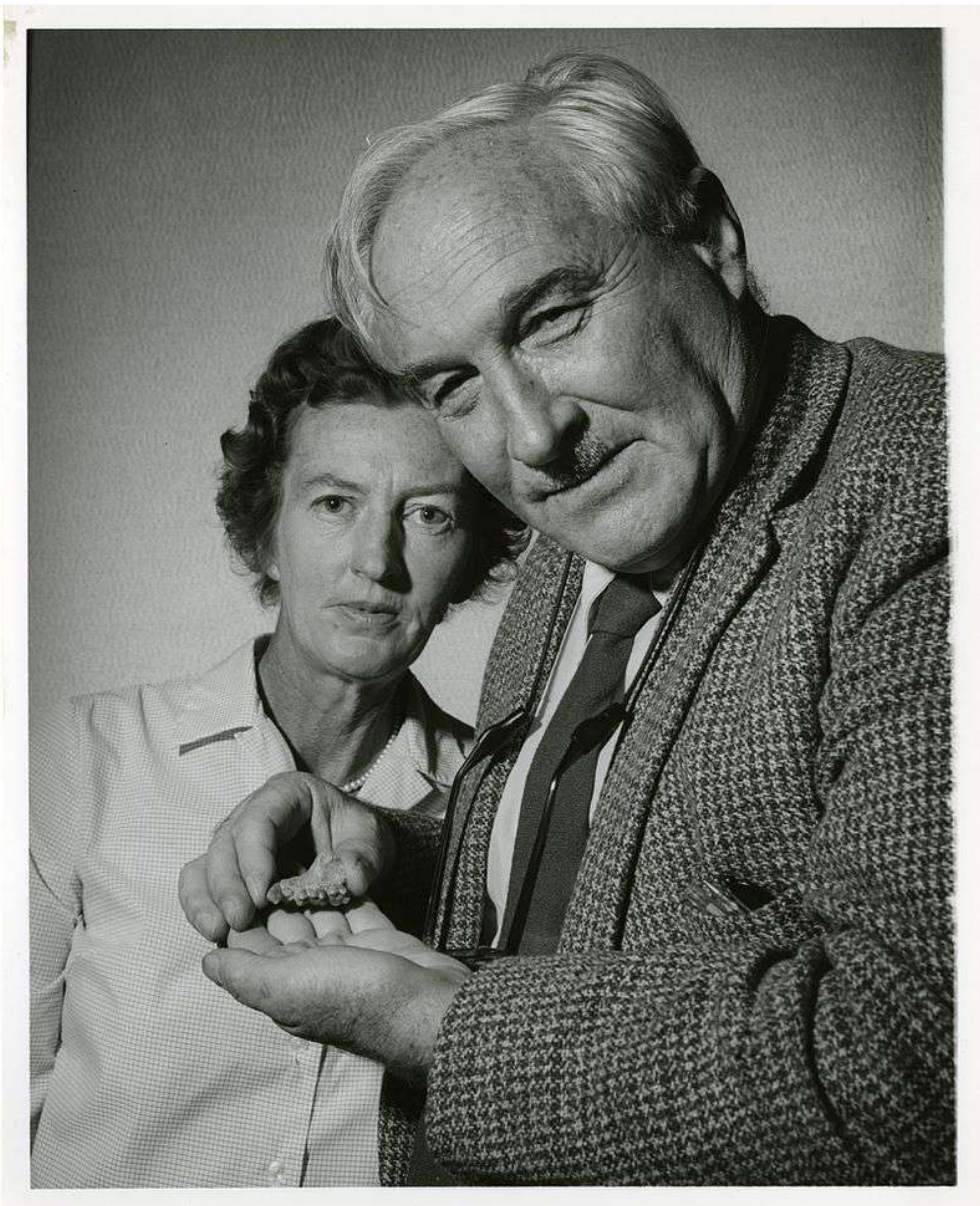


Figure 3.1: **Louis Leakey (1903-1972), with his wife and co-worker Mary.**

Figure 3.2: **Photograph of Dian Fossey by Yann Arthus-Bertrand. She studied the behavior of gorillas in their natural habitat.**

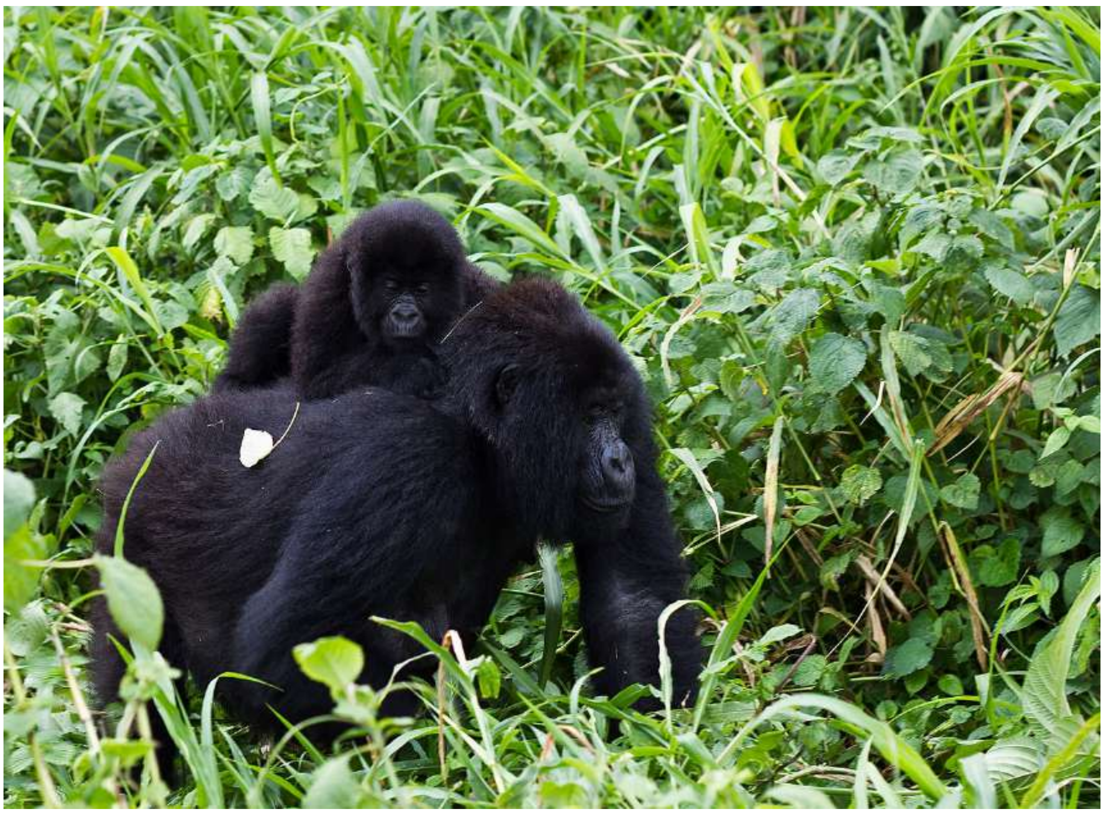


Figure 3.3: **Gorilla mother with infant in Virunga National Park in the Congo.**

Figure 3.4: **Professor Biruté Galdikas. She is known for her important studies of orangutans.**

3.2 Jane Goodall: Growing up with a love of animals

Jane Goodall was born in 1934, in the London suburb of Chelsea. Both of her parents came from relatively wealthy families. Her father was an engineer, and later a racing car driver, while her mother was a writer.

When Jane was about a year old, she was given a toy chimpanzee called Jubilee, which had been made by the London Zoo to celebrate their first birth of a chimpanzee in captivity. Among her many later toys, Jubilee remained her favorite. Jane also had many pet animals, including racing snails, caterpillars, a lizard, guinea pigs, a hamster and a canary.

Fascination with Africa

At elementary school in Bournemouth, Jane became an avid reader. Her favorite books were *Doctor Doolittle*, *The Jungle Book*, and *Tarzan* - all three books involving people who were very close to animals and could communicate with them. Jane began to dream of one day going to Africa. ,

3.3 Africa, Leakey and the search for early human behavior

Jane's chance to visit Africa came in 1955, when a school friend invited her to visit her family's farm in Kenya. It was not until 1957 that Jane had saved enough money for the journey. She travelled by ship, and the journey took three weeks; but when she arrived, Africa was everything that she had dreamed of. To prolong her stay, Jane took an office job in Nairobi, where, by a stroke of luck, she met the paleontologist Louis Leakey.

Leakey was impressed by Jane's enthusiasm and by her extremely wide knowledge of natural history. He asked her to be his secretary, but what he really had in mind was to hire her to investigate the behavior of wild chimpanzees, the closes relatives of humans, hoping that it would cast light on the behavior of early humans.

Figure 3.5: **Louis Leakey and Jane Goodall.**

Figure 3.6: **Jane Goodall with her husband, Baron Hugo van Lawick, a Dutch wildlife photographer sent to Gombe by The National Geographic.**

3.4 The Gombe research project

Searching for hominid fossils

Before starting secretarial work for Louis Leakey, Jane spent some time with the paleontologist and his wife Mary searching for fossil hominids in Tanzania. It was on this expedition that Leakey made his final decision that Jane would be his team's chimpanzee researcher in Gombe Park, Kenya.

Two women alone in the African bush

Following Leakey's advice, Jane returned to London in 1958 to consult with experts in the fields of primate anatomy and behavior. She was then 25 years old. By 1960, Leakey had raised enough money to fund her research, and she returned to Africa together with her mother, who stayed with her for the first few months. The two women were alone in the untamed wilderness. Gradually they became friends with the local fishermen and tribesmen. After her mother's departure, Jane (still more gradually) became accepted by Gombe Park's chimpanzee's, to whom she gave names, an unusual practice at the time.

Jane's key discoveries

- **Use of tools**: Jane discovered that chimpanzees make and use tools. For example, she observed a chimpanzee removing leaves from a twig in order to make an instrument for digging termites out of logs.

- **Hunting other animals and eating them**: Jane saw chimpanzees hunt and eat monkeys. Chimps had previously been thought to be vegetarians.

- **Chimpanzee troops wage war with rival troops**: Jane observed, for the first time, deadly territorial conflicts between chimpanzee troops. This observation casts troubling light on inherited human behavior.

- **Maternal behavior is learned**: Jane observed chimpanzee mothers teaching their daughters how to care for younger infants. She remarked, "We are not the only beings on the planet with personalities, thoughts, and - most importantly - feelings".

- **Hugging, kissing and body language**: Jane observed chimpanzees hugging and kissing each other, and using the same gestures that humans would use in similar situations. She states that "The nonverbal body language is the same for chimpanzees as it is for us. They use the same gestures and postures in the same context."

Books by Jane Goodall

- 1969 *My Friends the Wild Chimpanzees* Washington, DC: National Geographic Society

- 1971 *Innocent Killers (with H. van Lawick).* Boston: Houghton Mifflin; London: Collins.
- 1971 *In the Shadow of Man* Boston: Houghton Mifflin; London: Collins. Published in 48 languages.
- 1986 *The Chimpanzees of Gombe: Patterns of Behavior* Boston: Bellknap Press of the Harvard University Press. Published also in Japanese and Russian.
- 1990 *Through a Window: 30 years observing the Gombe chimpanzees* London: Weidenfeld & Nicolson; Boston: Houghton Mifflin. Translated into more than 15 languages. 1991 Penguin edition, UK.
- 1991 *Visions of Caliban* (co-authored with Dale Peterson, PhD). Boston: Houghton Mifflin.
- 1999 *Brutal Kinship* (with Michael Nichols). New York: Aperture Foundation.
- 1999 *Reason For Hope; A Spiritual Journey* (with Phillip Berman). New York: Warner Books, Inc. Translated into Japanese and Portuguese.
- 2000 *40 Years At Gombe* New York: Stewart, Tabori, and Chang.
- 2000 *Africa In My Blood* (edited by Dale Peterson). New York: Houghton Mifflin Company.
- 2002 *The Ten Trusts: What We Must Do To Care for the Animals We Love* (with Marc Bekoff). San Francisco: Harper San Francisco
- 2005 *Harvest for Hope: A Guide to Mindful Eating* New York: Warner Books, Inc.
- 2009 *Hope for Animals and Their World: How Endangered Species Are Being Rescued from the Brink* Grand Central Publishing
- 2013 *Seeds of Hope: Wisdom and Wonder from the World of Plants* (with Gail Hudson) Grand Central Publishing

Children's books by Jane Goodall

- 1972 *Grub: The Bush Baby* (with H. van Lawick). Boston: Houghton Mifflin.
- 1988 *My Life with the Chimpanzees* New York: Byron Preiss Visual Publications, Inc. Translated into French, Japanese and Chinese.
- 1989 *The Chimpanzee Family Book* Saxonville, MA: Picture Book Studio; Munich: Neugebauer Press; London: Picture Book Studio. Translated into more than 15 languages, including Japanese and Swahili.
- 1989 *Jane Goodall's Animal World: Chimps* New York: Macmillan.
- 1989 *Animal Family Series: Chimpanzee Family; Lion Family; Elephant Family; Zebra Family; Giraffe Family; Baboon Family; Hyena Family; Wildebeest Family* Toronto: Madison Marketing Ltd.
- 1994 *With Love* New York / London: North-South Books. Translated into German, French, Italian, and Japanese.
- 1999 *Dr. White* (illustrated by Julie Litty). New York: North-South Books.
- 2000 *The Eagle* & *the Wren* (illustrated by Alexander Reichstein). New York: North-South Books.
- 2001 *Chimpanzees I Love: Saving Their World and Ours* New York: Scholastic Press

- 2004 *Rickie and Henri: A True Story* (with Alan Marks) Penguin Young Readers Group

Films

- 1965 *Miss Goodall and the Wild Chimpanzees* National Geographic Society
- 1975 *Miss Goodall: The Hyena Story* The World of Animal Behavior Series 16mm 1979 version for DiscoVision, not released for LaserDisc
- 1984 *Among the Wild Chimpanzees* National Geographic Special
- 1988 *People of the Forest* with Hugo van Lawick
- 1990 *Chimpanzee Alert* in the Nature Watch Series, Central Television
- 1990 *The Life and Legend of Jane Goodall* National Geographic Society.
- 1990 *The Gombe Chimpanzees* Bavarian Television
- 1995 *Fifi's Boys* for the Natural World series for the BBC
- 1996 *Chimpanzee Diary* for BBC2 Animal Zone
- 1997 *Animal Minds*for BBC
- Goodall voiced herself in the animated TV series *The Wild Thornberrys.*
- 2000 *Jane Goodall: Reason For Hope* PBS special produced by KTCA
- 2001 *Chimps R Us*, on season 11, episode 8. Scientific American Frontiers. Chedd-Angier Production Company.
- 2002 *Jane Goodall's Wild Chimpanzees* (IMAX format), in collaboration with Science North
- 2005 *Jane Goodall's Return to Gombe* for Animal Planet
- 2006 *Chimps, So Like Us* HBO film nominated for 1990 Academy Award
- 2007 *When Animals Talk We Should Listen*, theatrical documentary feature co-produced by Animal Planet
- 2010 *Jane's Journey.* theatrical documentary feature co-produced by Animal Planet
- 2012 *Chimpanzee*, theatrical nature documentary feature co-produced by Disneynature
- 2017 *Jane*, biographical documentary film National Geographic Studios, in association with Public Road Productions. The film is directed and written by Brett Morgen, music by Philip Glass

Suggestions for further reading

1. Meg Greene Jane Goodall: A Biography Greenwood Publishing Group, 2005
2. Dale Peterson *Jane Goodall: The Woman who Redefined Man* Houghton Mifflin Harcourt, 2006
3. Lynn Margulis, Eduardo Punset *Mind, Life and Universe: Conversations with Great Scientists of Our Time* Chelsea Green Publishing, 2007
4. Goodall, Jane; Peterson, Dale. *Beyond Innocence: An Autobiography in Letters: The Later Years.* Houghton Mifflin Harcourt, (25 September 2002)

Chapter 4

THE FIRST HUMANS IN AUSTRALIA

4.1 Across the open water to Australia

In an article entitled *How Did the First People Get to Australia?*, published on April 2, 2018 by RealClear Science, Kasih Norman wrote:

"The First Australians were among the world's earliest great ocean explorers, undertaking a remarkable 2,000km maritime migration through Indonesia which led to the discovery of Australia at least 65,000 years ago.

"But the voyaging routes taken through Indonesia's islands, and the location of first landfall in Australia, remain a much debated mystery to archaeologists.

"Our research, published earlier this year in Quaternary Science Reviews, highlights the most likely route by mapping islands in the region over time through changing sea levels.

"The rise in global ocean levels at the end of the last ice age at around 18,000 years ago flooded continental shelves across the world, reshaping landmasses. This event drowned the ancient continent of Sunda, creating many of Indonesia's islands, and split the continent of Sahul into Australia and New Guinea.

"This means that what is now under the ocean is very important to understanding where the First Australians might have made landfall.

"When people first migrated to Indonesia, reaching Australia by 65,000 years ago, they found a landscape that looked very different from today. During an ice age known as Marine Isotope Stage 4, which stretched from roughly 71,000 to 59,000 years ago, western Indonesia formed part of the Pleistocene continent of Sunda, while Australia and New Guinea were joined to form Sahul."

The maps shown below are taken from Kasih Norman's article. They show what the first Australians could have seen across the water before embarking in their boats.

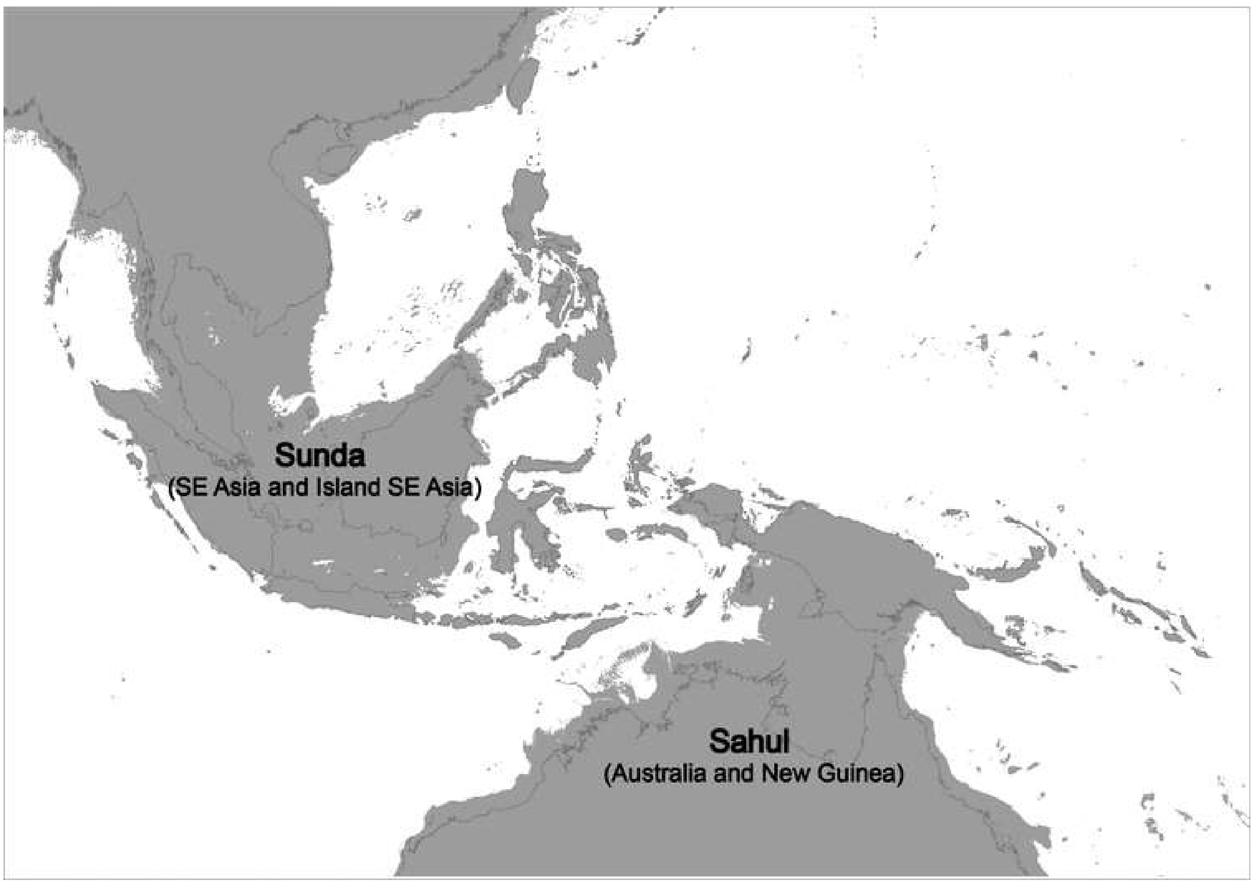
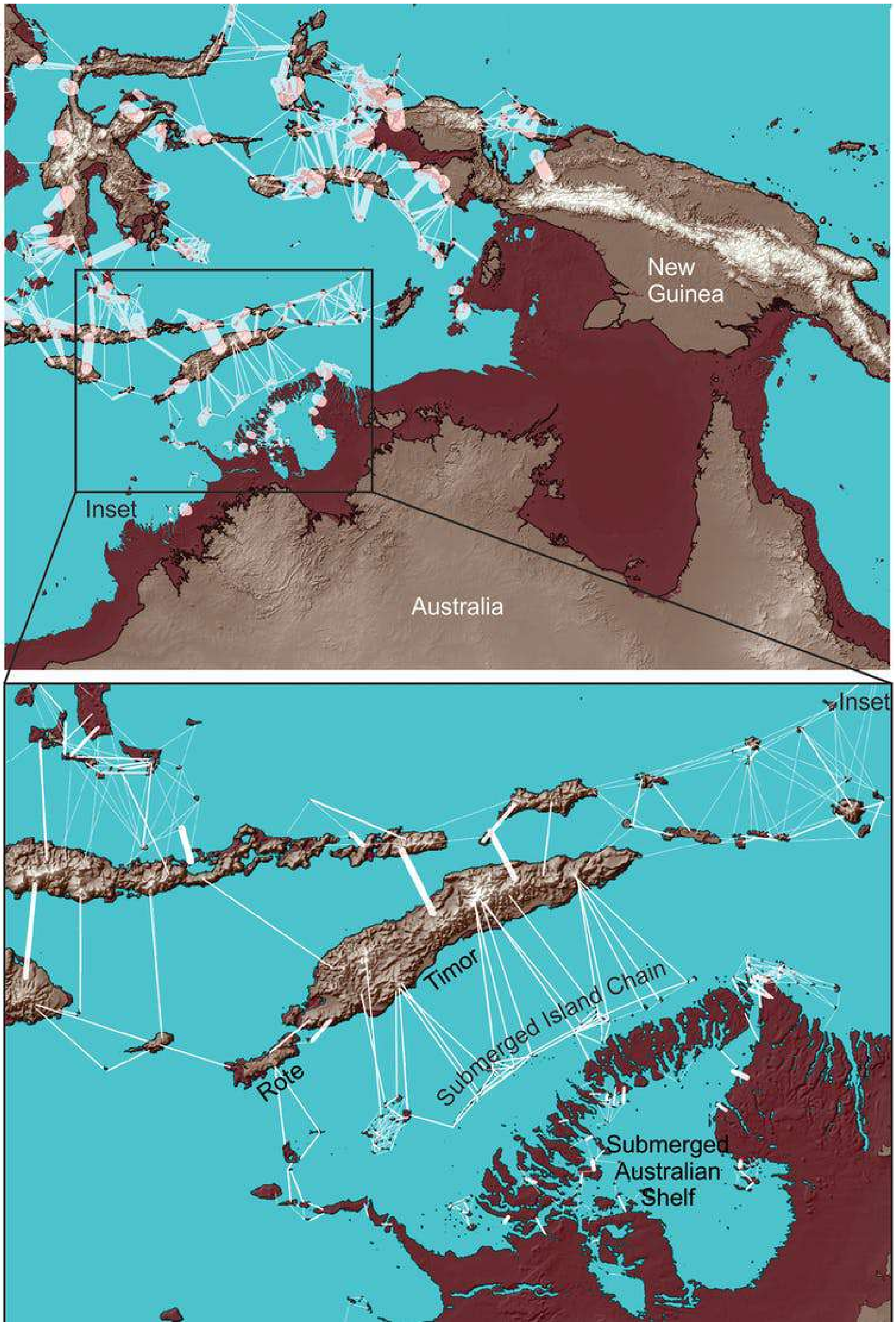


Figure 4.1: **The grey area shows the extent of the ice age continents of Sunda and Sahul, much of which is now under water.**


New
Guinea
Inset
Australia
Inset
Timor
Rote
Submerged Island Chain
Submerged
Australian
Shelf

4.2 Fire farming and megafauna extinctions

There is evidence that the original Australians used fire to change the character of the landscape and to increase their food supply. This practice probably contributed to the extinction of megafauna in Australia.

According to Wikipedia,

"Archaeological evidence from ash deposits in the Coral Sea indicates that fire was already a significant part of the Australian landscape over 100,000 years BP. Over the past 70,000 years it became more frequent with one explanation being the use by hunter-gatherers as a tool to drive game, to produce a green flush of new growth to attract animals, and to open up impenetrable forest. In The Biggest Estate on Earth: How Aborigines made Australia, Bill Gammage claims that dense forest became more open sclerophyll forest, open forest became grassland and fire-tolerant species became more predominant: in particular, eucalyptus, acacia, banksia, casuarina and grasses.

"The changes to the fauna were even more dramatic: the megafauna, species significantly larger than humans, disappeared, and many of the smaller species disappeared too. All told, about 60 different vertebrates became extinct, including the genus *Diprotodon* (very large marsupial herbivores that looked rather like hippos), several large flightless birds, carnivorous kangaroos, *Wonambi naracoortensis*, a five-metre snake, a five-metre lizard and *Meiolania*, a tortoise the size of a small car.

"The direct cause of the mass extinctions is uncertain: it may have been fire, hunting, climate change or a combination of all or any of these factors."

Suggestions for further reading

1. David Frankel (2017). *Between the Murray and the Sea. Aboriginal Archaeology in Southeastern Australia.* Sydney University Press.
2. Geoffrey Blainey (1976). *Triumph of the Nomads: History of Ancient Australia.* Palgrave Macmillan UK.
3. Harry Lourandos (1997). *Continent of Hunter-Gatherers: New Perspectives in Australian Prehistory.* Cambridge University Press.
4. D. J. Mulvaney (1969). *The Prehistory of Australia.* London: Thames and Hudson.
5. John Mulvaney; Johan Kamminga; Brissenden collection (1999). *Prehistory of Australia.* Allen & Unwin.
6. Jennifer Isaacs (2006). *Australian Dreaming: 40,000 Years of Aboriginal History.* New Holland.
7. Ronald M. Berndt (2005) [1952]. *Djanggawul: An Aboriginal Religious Cult of North-Eastern Arnhem Land.* Routledge.
8. Tony Swain (1993). *A place for strangers: towards a history of Australian Aboriginal being.* Cambridge University Press.

Chapter 5

THE FIRST DISCOVERY OF AMERICA

5.1 Early migration across the Bering Strait

The continents of North America and South America have been discovered many times by humans. Figure 1.1 shows the path of the first migrations across the Bering Strait during a glacial period. These migrations are thought to have started approximately 20,000 years ago. The interiors of present-day Alaska and Canada were at that time entirely covered by a thick ice sheet, but archaeological evidence shows that these first Americans had boats and moved along the coast, living from fishing and from gathering shellfish.

During a glacial period between 20,000 and 10,000 years before the present, there was a land bridge across the Bering Strait. There is evidence that humans crossed this land bridge from Siberia and followed a coastal route past the glaciated regions of what is now Canada, finally reaching South America. Humans were able to build boats at that time, as evidenced by traces of very early settlements on islands off the coast of South America.

In a May 24, 2017 article in *Science*, Lizzie Wade wrote:

"About 600 kilometers north of Lima, an imposing earthen mound looms over the sea. People began building the ceremonial structure, called Huaca Prieta, about 7800 years ago. But according to a new study, the true surprise lies buried deep beneath the 30-meter-tall mound: stone tools, animal bones, and plant remains left behind by some of the earliest known Americans nearly 15,000 years ago. That makes Huaca Prieta one of the oldest archaeological sites in the Americas and suggests that the region's first migrants may have moved surprisingly slowly down the coast.

"The evidence of early human occupation stunned Tom Dillehay, an archaeologist at Vanderbilt University in Nashville who led the new study. Initially, he was interested in examining the mound itself. But geologists on his team wanted to study the land-form under the mound, so 'we just kept going down,' he says. The deepest pit, which took 5 years to excavate, reached down 31 meters. Shockingly, those deep layers contained telltale

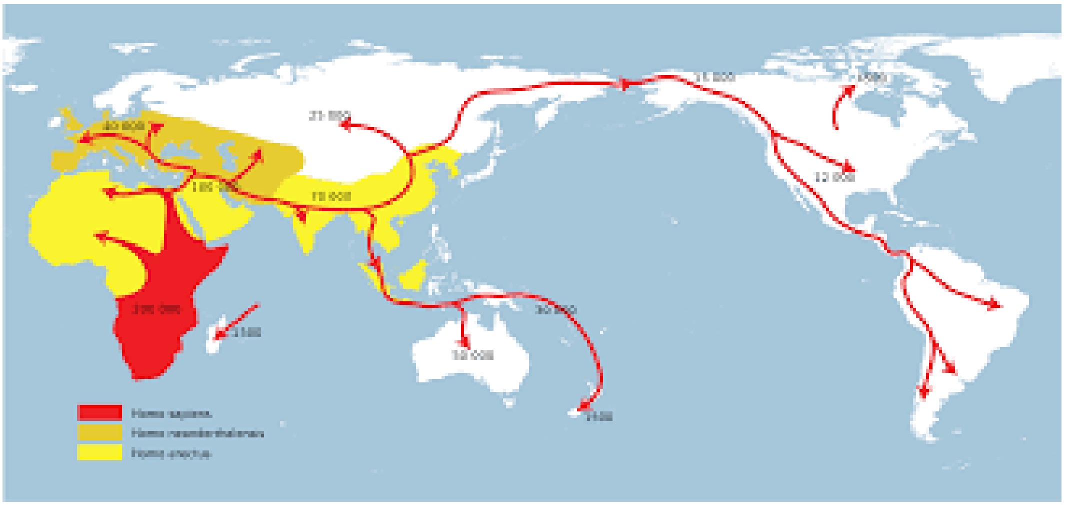


Figure 5.1: **The spread of Homo sapiens**

signs of human occupation, Dillehay's team reports today in Science Advances: evidence of hearth fires, animal bones, plant remains, and simple but unmistakable stone tools. Radiocarbon dates from charcoal place the earliest human occupation at nearly 15,000 years ago.

"That's made some researchers say Huaca Prieta should join the small but growing list of pre-14,000-year-old sites that have revolutionized scientists' vision of the earliest Americans. Archaeologists used to think that people walked from Siberia through an ice-free passage down Alaska and Canada, reaching the interior of the United States about 13,000 years ago. In recent years, however, well documented earlier sites like Chile's Monte Verde have convinced most archaeologists that humans made it deep into the Americas by 14,500 years ago, meaning that they would have had to cross Canada long before an ice-free corridor existed. That would have left them with one logical route into the Americas: down the Pacific coast. But direct evidence for such a migration is lacking."

Another site that shows evidence of early human presence is Piki Mach'ay cave in Peru Radiocarbon dates from this cave give a human presence ranging from 22,200 to 14,700 years ago, but this evidence has been disputed. Wikipedia states that "Piki Mach'ay yielded some of the oldest plant remains in Peru, including an 11,000 year old bottle gourd. Strata from later periods at the site revealed fishtail points, manos, and metates. Plant remains indicate that, before 3,000 years BCE, amaranth, cotton, gourds, lucuma, quinoa, and squash were cultivated in the Ayacucho Basin before 3,000 years BCE. By 4,000 years BCE corn (Zea mays) and common beans were grown. Chili remains date from 5,500 to 4,300 years BCE. The large amounts of guinea pig bones suggest possible domestication, and llamas may have been domesticated by 4,300 to 2,800 years BCE."

Figure 5.2: **An artist's guess at what the inhabitants of Piki Mach'ay cave in Peru might have looked like.**

5.2 The discoveries of Peter Wilhelm Lund

Peter Wilhelm Lund (1801-1880) is considered to be "the father of Brazilian paleontology and archeology". He was born in Copenhagen, into a wealthy family. Peter Lund's father wished him to study medicine, but following the death of his father, Lund followed his passion for natural history and studied this subject at the University of Copenhagen. While still a student, he wrote two prize-winning dissertations, one of which gained him international recognition.

In 1825 Lund travelled to Brazil for the sake of his health, because he was showing signs of tuberculosis. During the next three years, he studied and collected plants, birds and insects from the region near to Rio de Janero. Then, returning to Europe, he obtained a Doctor's degree from the University of Kiel. He also spent some time in Paris, where he was greatly influenced by Georges Cuvier and his Catastrophist Theory.

In 1832, Lund returned to Brazil, where he spent the remainder of his life. This time, he discovered caves in Lagoa which contained the bones of extinct megafauna, for example the famous "saber-toothed tiger", which he was the first to describe. In the same caves, he also found the bones of humans, thus proving that humans had arrived at the region at a very early date, Lund seemed perplexed and worried by his own discoveries. However, they were embraced with enthusiasm by his contemporary, Charles Darwin.

Figure 5.3: **A portrait of Peter Wilhelm Lund.**

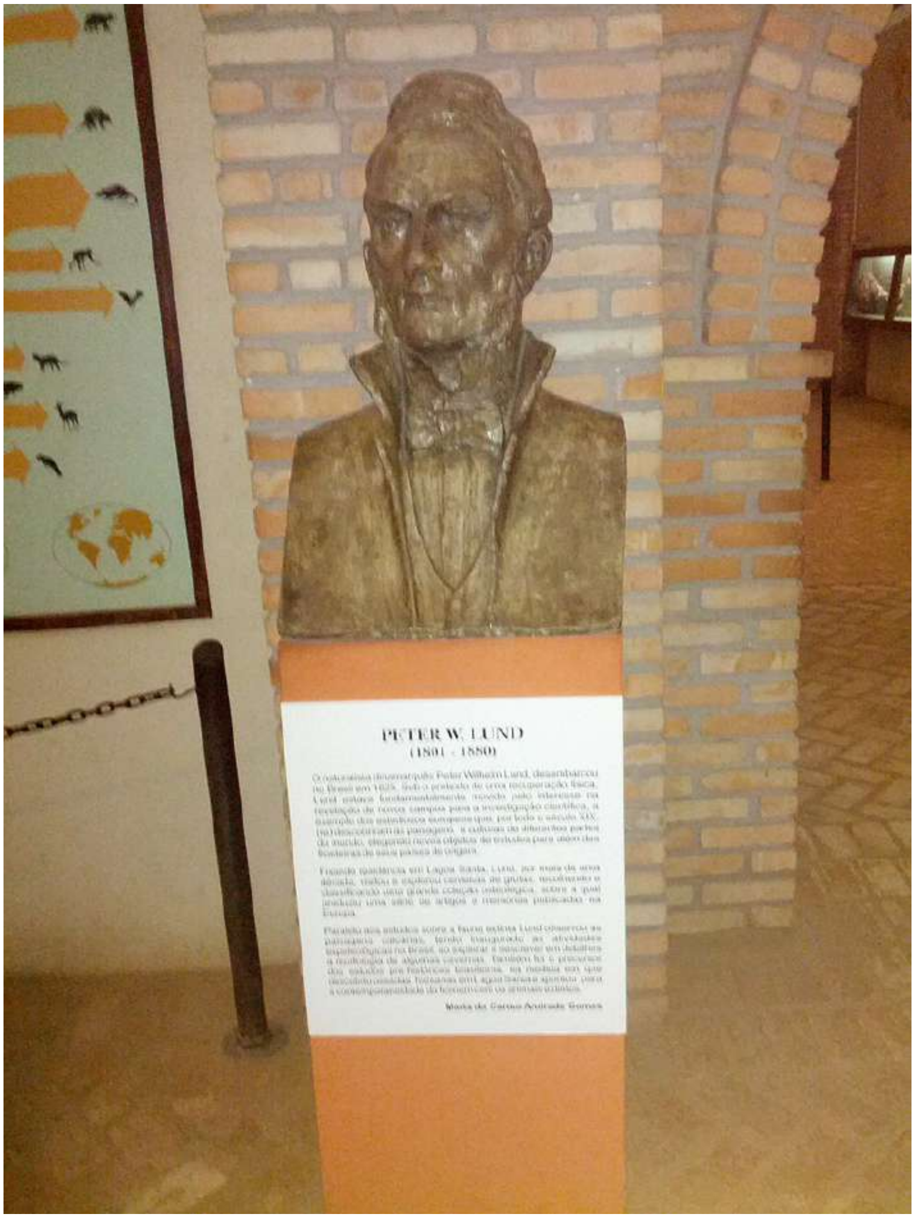


Figure 5.4: **Statue of Lund at Natural History Museum and Botanical Garden of Universidade Federal de Minas Gerais.**

Figure 5.5: **Smilodon populator skull and syntype canine from Lund's collection, Zoological Museum, Copenhagen. Peter Lund was the first to describe the extinct "saber-tooted tiger". Lund found the bones of humans in Brazilian caves together with the bones of extinct animals, This discovery proved that humans arrived in South America at a very early date.**

Suggestions for further reading

1. Bradley, B.; Stanford, D. (2004). *The North Atlantic ice-edge corridor: a possible Palaeolithic route to the New World*. World Archaeology. 36 (4): 459-478.
2. Bradley, B.; Stanford, D. (2006). *The Solutrean-Clovis connection: reply to Straus, Meltzer and Goebel*. World Archaeology. 38 (4): 704-714.
3. Dennis J. Stanford, Bruce Bradely, *Pre-Clovis First Americans: The Origin of America's Clovis Culture* (University of California Press, 2012).
4. Dennis J. Stanford, Bruce A. Bradley, *Across Atlantic Ice: The Origin of America's Clovis Culture* (University of California Press (2012).
5. Dixon, E. James. *Quest for the Origins of the First Americans*. University of New Mexico Press. 1993.
6. Dixon, E. James. Bones, *Boats, and Bison: the Early Archeology of Western North America*. University of New Mexico Press. 1993, 1999.
7. Erlandson, Jon M. *Early Hunter-Gatherers of the California Coast*. Plenum Press. 1994.
8. Erlandson, Jon M (2001). *The Archaeology of Aquatic Adaptations: Paradigms for a New Millennium*. Journal of Archaeological Research. 9 (4): 287-350.
9. Erlandson, Jon M. *Anatomically Modern Humans, Maritime Migrations, and the Peopling of the New World. In The First Americans: The Pleistocene Colonization of the New World*, edited by N. Jablonski, 2002. pp. 59-92. Memoirs of the California Academy of Sciences. San Francisco.
10. Erlandson, Jon. M.; Graham, M. H.; Bourque, Bruce J.; Corbett, Debra; Estes, James A.; Steneck, R. S. (2007). *The Kelp Highway Hypothesis: Marine Ecology, The Coastal Migration Theory, and the Peopling of the Americas*. Journal of Island and Coastal Archaeology. 2 (2): 161-174.
11. Eshleman, Jason A.; Malhi, Ripan S.; Glenn Smith, David (2003). *Mitochondrial DNA Studies of Native Americans: Conceptions and Misconceptions of the Population Prehistory of the Americas*. Evolutionary Anthropology. 12: 7-18.
12. Fedje; Christensen (1999). *Modeling Paleoshorelines and Locating Early Holocene Coastal Sites in Haida Gwaii*. American Antiquity. 64 (4): 635-652.
13. Greenman, E. F. (1963). *The Upper Palaeolithic and the New World*. Current Anthropology. 4: 41-66.
14. Hey, Jody (2005). *On the Number of New World Founders: A Population Genetic Portrait of the Peopling of the Americas*. PLOS Biology. 3 (6).
15. Nina G. Jablonski (2002). *The First Americans: The Pleistocene Colonization of the New World*. California Academy of Sciences. ISBN 978-0-940228-50-4.
16. Jones, Peter N. *Respect for the Ancestors: American Indian Cultural Affiliation in the American West*. Boulder, Colorado: Bauu Press. 2004, 2005.
17. Korotayev, Andrey et al. *Which genes and myths did the different waves of the peopling of Americas bring to the New World?*. History and Mathematics 6 (2017): 9-77.

18. Lauber, Patricia. *Who Came First? New Clues to Prehistoric Americans*. Washington, D.C.: National Geographic Society, 2003.
19. Matson and Coupland. *The Prehistory of the Northwest Coast*. Academic Press. New York. 1995.
20. David J. Meltzer (2009). *First Peoples in a New World: Colonizing Ice Age America.* University of California Press.
21. Snow, Dean R. *The First Americans and the Differentiation of Hunter-Gatherer Cultures.* In Bruce G. Trigger and Wilcomb E. Washburn, eds., *The Cambridge History of the Native Peoples of the Americas*, Volume I: North America (Cambridge: Cambridge University Press, 1996), 125-199.
22. Spencer Wells (2002). *The Journey of Man: A Genetic Odyssey.* Princeton University Press.

Chapter 6

PREHISTORIC PAINTING

6.1 Cave painting in Europe

Lascaux

The prehistoric paintings from the Lascaux cave in southern France shown below depict the animals which were hunted by the artists. This suggests that paintings may have been made in the belief that they would help the success of the hunt.

6.2 Rock painting in Northern Africa

The climate in northern Africa was once much wetter and cooler than it now is. The existence of numerous rock paintings in northern Africa testifies to the fact that a large population was once able to inhabit an area that now is a desert.

6.3 Rock painting in Australia

Aboriginal rock paintings in Australia are closely connected with the history of the community and with religion.

Figure 6.1: **A cave painting showing European bison.**

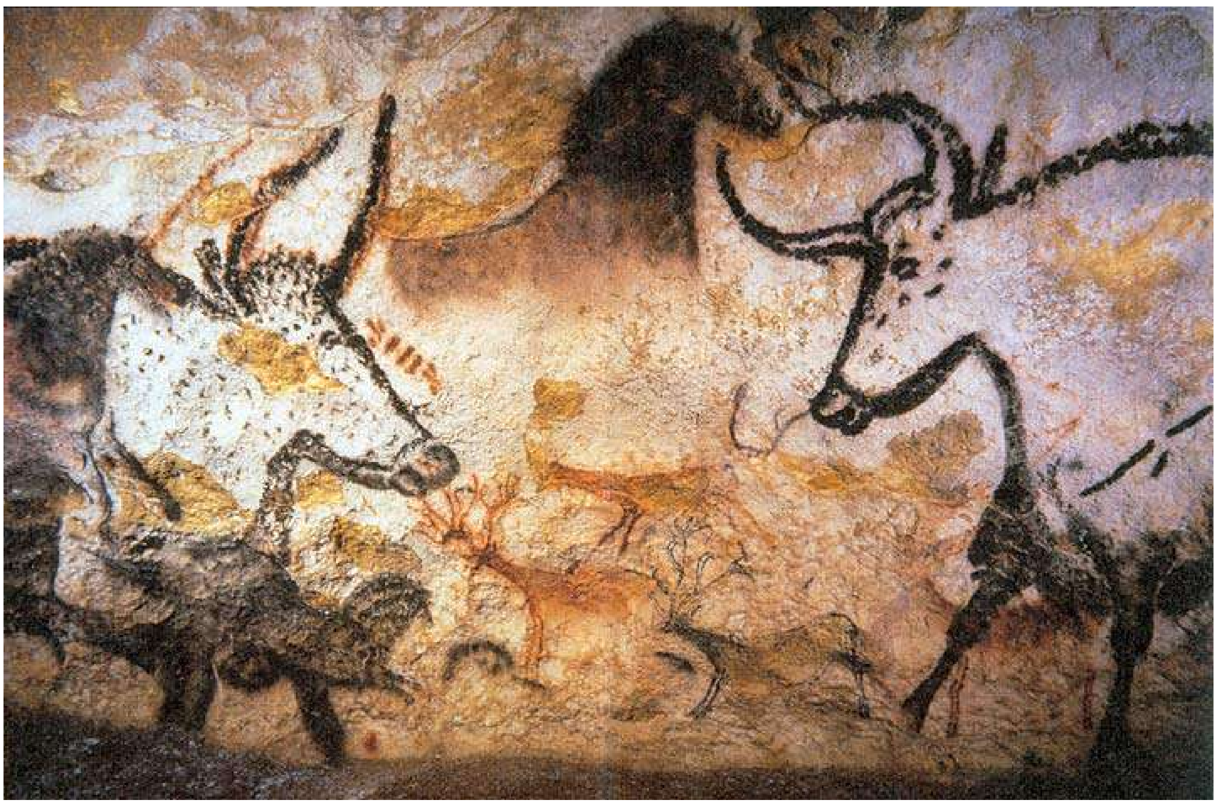


Figure 6.2: **Cave painting from the cave of Lascaux, France. The painting shows aurochs, horses and deer, and is estimated to be around 17,000 years old. Over 600 paintings cover the interior of the cave.**

Figure 6.3: **Another painting from Lascaux, showing a horse.**

Figure 6.4: **A third painting from Lascaux: Megaloceros with a line of dots.**

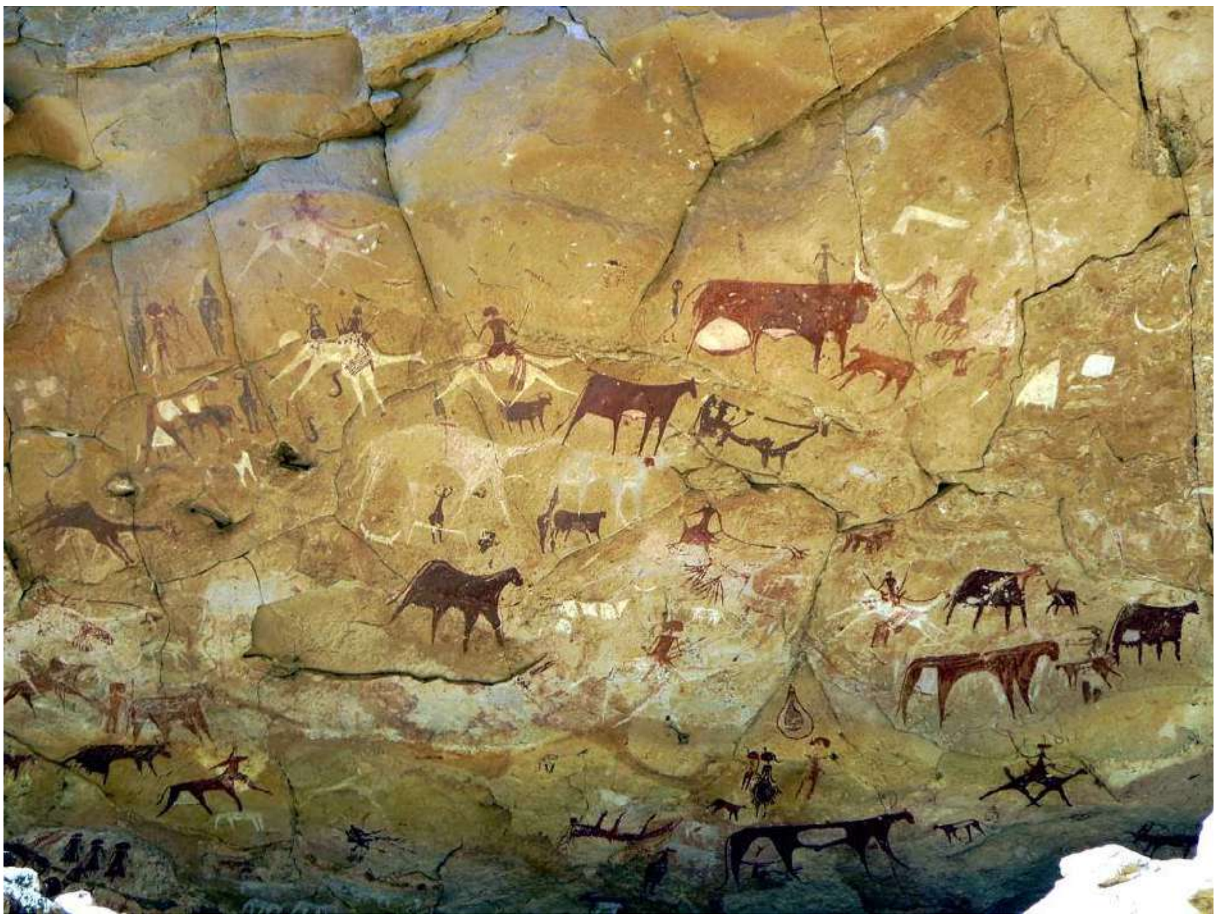


Figure 6.5: **Prehistoric rock paintings in Manda Guéli Cave in the Ennedi Mountains, Chad, Central Africa. Camels have been painted over earlier images of cattle, perhaps reflecting climatic changes.**

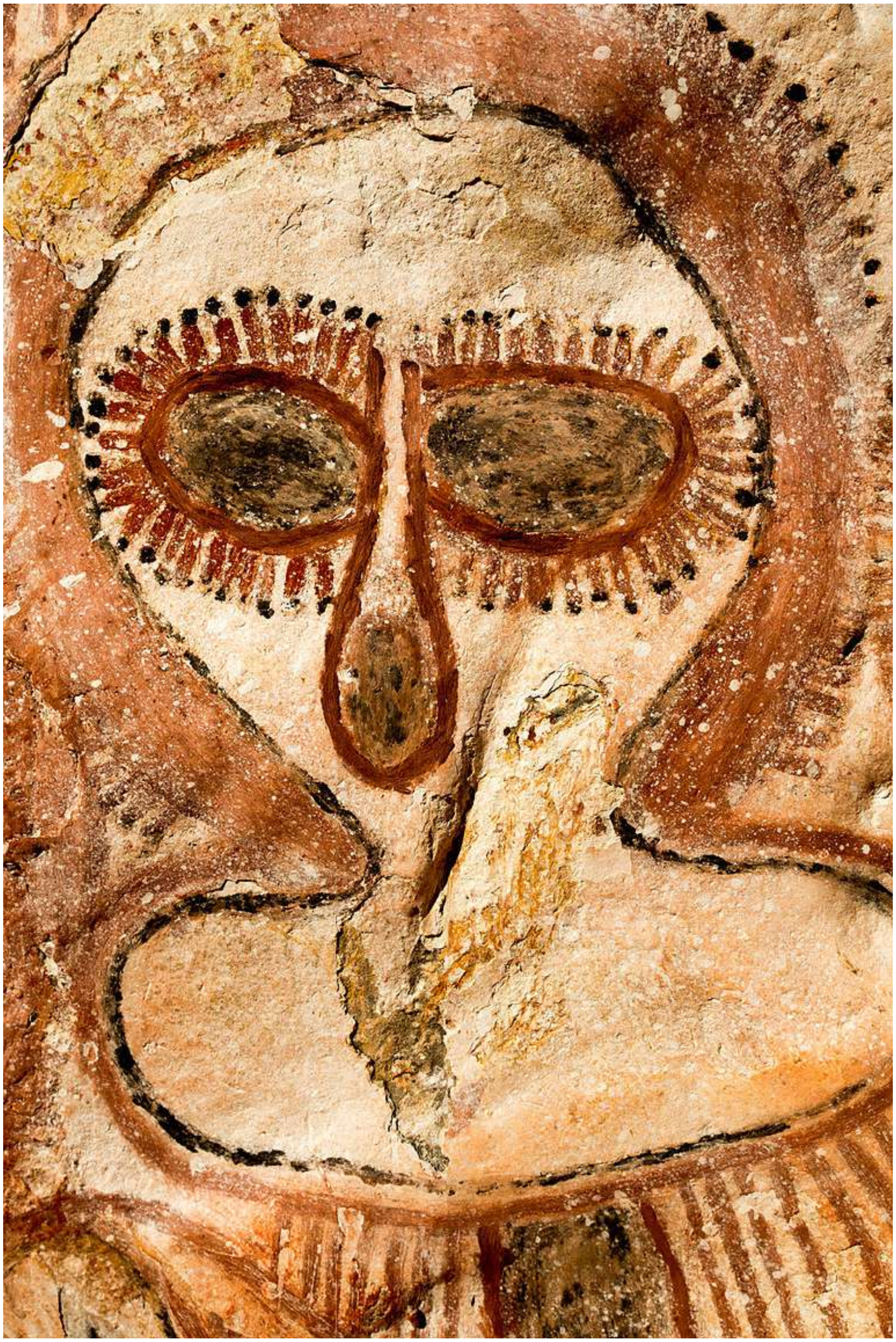
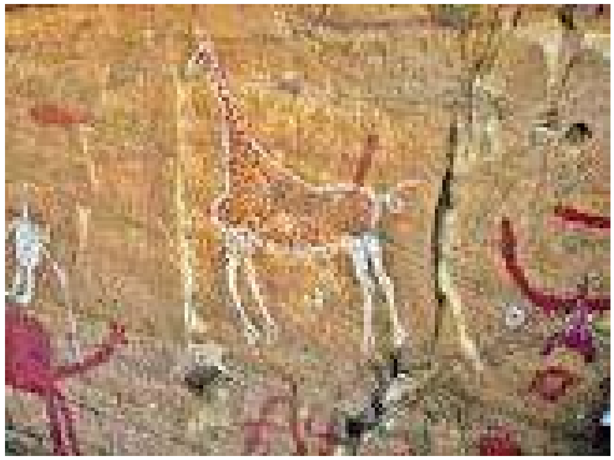
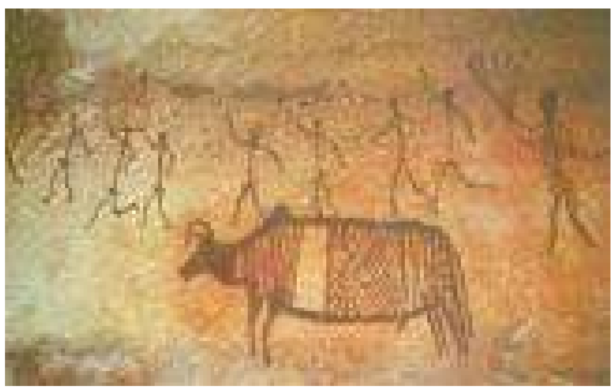


Figure 6.6: **Wondjina, an Australian aboriginal painting, approximately 4,000 years old, from the Barnett River, Mount Elizabeth Station. Wondjina are the cloud and rain spirits from Australian Aboriginal mythology. Below are some untitled prehistoric paintings.**





Suggestions for further reading

1. Dubowski, Mark (2010). *Discovery in the Cave* (Children's early reader). New York, USA: Random House.
2. Fage, Luc-Henri; Chazine, Jean-Michel (2010). *Borneo - Memory of the Caves*. Le Kalimanthrope.
3. Heyd, Thomas; Clegg, John, eds. (2005). *Aesthetics and Rock Art*. Ashgate Publishing.
4. Curtis, Gregory (2006). *The Cave Painters: Probing the Mysteries of the World's First Artists*.
5. Nechvatal, Joseph (2005). *Immersive Excess in the Apse of Lascaux*. Technonoetic Arts. 3 (3): 181-192.

Chapter 7

PREHISTORIC MEGALITHIC STRUCTURES

7.1 Timeline

- c. 9500 BCE: Construction in Asia Minor (Göbekli Tepe); from proto-Hattian or else a yet-to-be-discovered culture (the oldest religious structure in the world).
- Submerged by around 7400 BCE: a 12m long monolith probably weighing around 15000 kg found 40m under water in the Strait of Sicily south-west of Sicily whose function is unknown
- c. 7000 BCE: Construction in proto-Canaanite Israel (Atlit Yam). Possibly first standing stones in Portugal.
- c. 6000 BCE: Constructions in Portugal (Almendres Cromlech, Évora)
- c. 5000 BCE: Emergence of the Atlantic Neolithic period, the age of agriculture along the western shores of Europe during the sixth millennium BC pottery culture of La Almagra, Spain near by, perhaps precedent from Africa.
- c. 4800 BCE: Constructions in Brittany, France (Barnenez) and Poitou (Bougon).
- c. 4500 BCE: Constructions in south Egypt (Nabta Playa).
- c. 4300 BCE: Constructions in south Spain (Dolmen de Alberite, CÃ¡diz).
- c. 4000 BCE: Constructions in Brittany (Carnac), Portugal (Great Dolmen of Zambujeiro, Évora), France (central and southern), Corsica, Spain (Galicia), England and Wales, Constructions in Andalusia, Spain (Villa MartÃn, CÃ¡diz), Construction in proto-Canaanite Israel c. 4000-3000 BC: Constructions in the rest of the proto-Canaanite Levant, e.g. Rujm el-Hiri and dolmens.
- c. 3700 BCE: Constructions in Ireland (Knockiveagh and elsewhere).
- c. 3600 BCE: Constructions in Malta (Skorba temples).
- c. 3600 BCE: Constructions in England (Maumbury Rings and Godmanchester), and Malta (Ä gantija and Mnajdra temples).
- c. 3500 BCE: Constructions in Spain (MÃ¡laga and Guadiana), Ireland (south-west), France (Arles and the north), Malta (and elsewhere in the Mediterranean), Belgium (north-east), and Germany (central and south-west).

- c. 3400 BCE: Constructions in Sardinia (circular graves), Ireland (Newgrange), Netherlands (north-east), Germany (northern and central) Sweden and Denmark.
- c. 3300 BCE: Constructions in France (Carnac stones)
- c. 3200 BCE: Constructions in Malta (Hagar Qim and Tarxien).
- c. 3100 BCE: Constructions in Russia (Dolmens of North Caucasus)
- c. 3000 BCE: Constructions in Sardinia (earliest construction phase of the prehistoric altar of Monte d'Accoddi), France (Saumur, Dordogne, Languedoc, Biscay, and the Mediterranean coast), Spain (Los Millares), Sicily, Belgium (Ardennes), and Orkney, as well as the first henges (circular earthworks) in Britain.
- c. 2500 BCE: Constructions in Brittany (Le Menec, Kermario and elsewhere), Italy (Otranto), Sardinia, and Scotland (northeast), plus the climax of the megalithic Bell-beaker culture in Iberia, Germany, and the British Isles (stone circle at Stonehenge). With the bell-beakers, the Neolithic period gave way to the Chalcolithic, the age of copper.
- c2500 BCE: Tombs at Algarve, Portugal. Additionally, a problematic dating (by optically stimulated luminescence) of Quinta da Queimada Menhir in western Algarve indicates "a very early period of megalithic activity in the Algarve, older than in the rest of Europe and in parallel, to some extent, with the famous Anatolian site of Göbekli Tepe"
- c. 2400 BCE: The Bell-beaker culture was dominant in Britain, and hundreds of smaller stone circles were built in the British Isles at this time.
- c. 2000 BCE: Constructions in Brittany (Er Grah), Italy : (Bari); Sicily (Cava dei Servi, Cava Lazzaro);, and Scotland (Callanish). The Chalcolithic period gave way to the Bronze Age in western and northern Europe.
- c. 1800 BCE: Constructions in Italy (Giovinazzo, in Sardinia started the nuragic civilization).
- c. 1500 BCE: Constructions in Portugal (Alter Pedroso and Mourela).
- c. 1400 BCE: Burial of the Egtved Girl in Denmark, whose body is today one of the best-preserved examples of its kind.
- c. 1200 BCE: Last vestiges of the megalithic tradition in the Mediterranean and elsewhere come to an end during the general population upheaval known to ancient history as the Invasions of the Sea Peoples.

7.2 Stonehenge

Figure 7.1: **Stonehenge, Wiltshire, United Kingdom, is one of the world's best known megalithic structures (constructed between 3100-2200 BCE).**

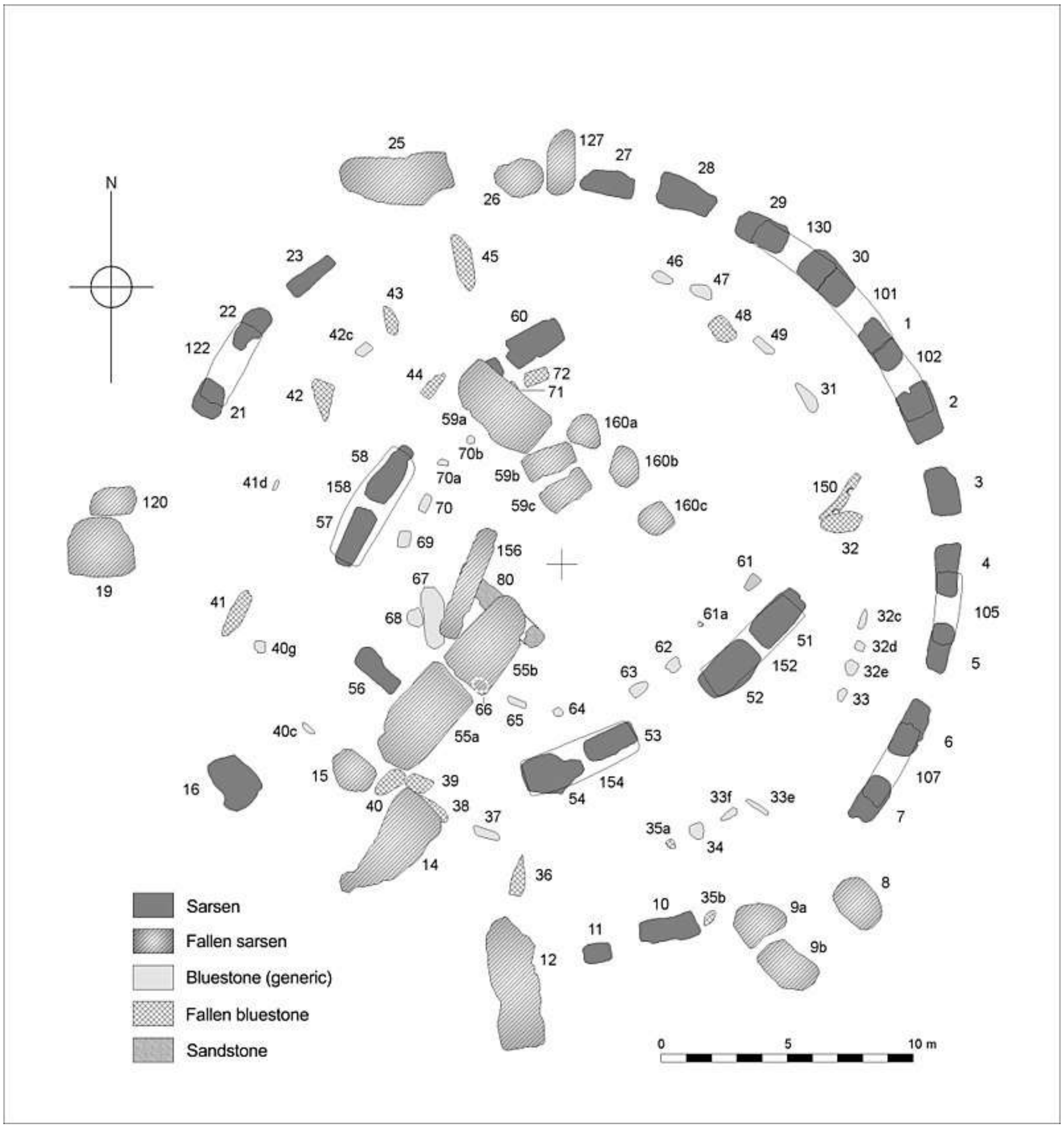


Figure 7.2: **Plan of the central stone structure today; after Johnson 2008.**

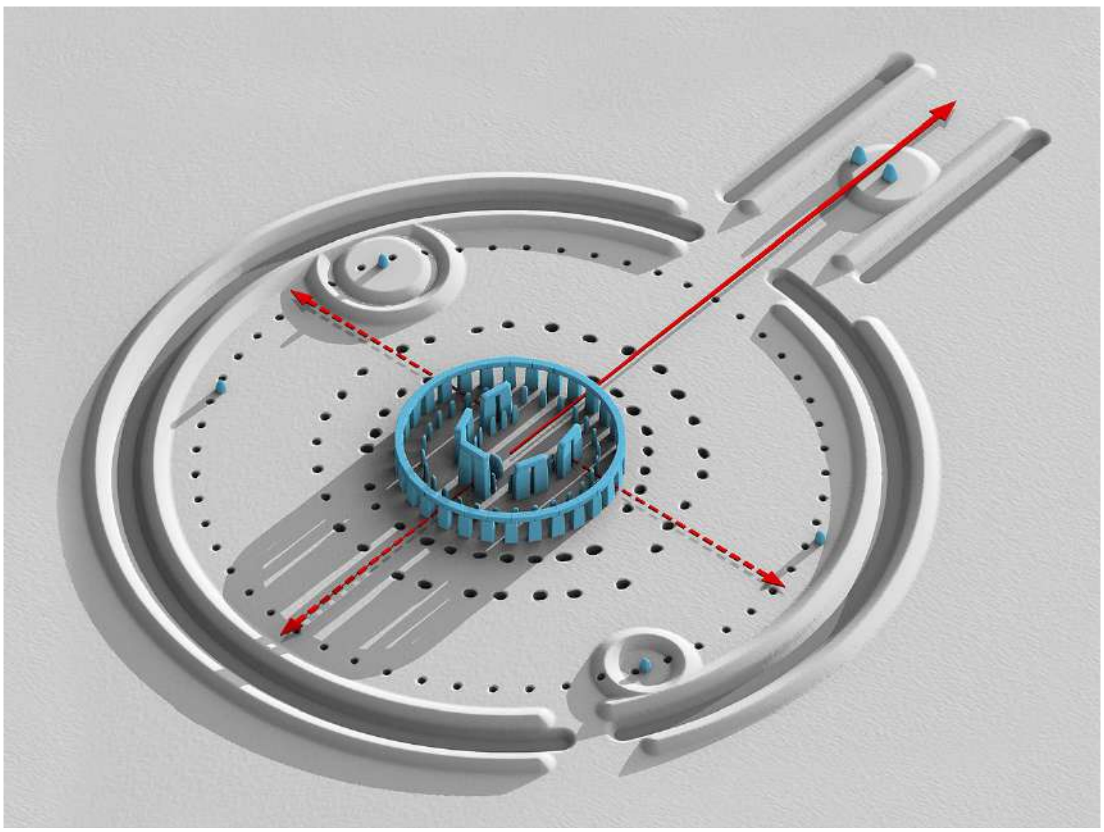


Figure 7.3: **Computer rendering of the overall site.**

7.3 Megalithic structures elswhere in the world

Figure 7.4: **The formations at Göbekli Tepe, in southeast Turkey, are the oldest (c9000 BCE) known megalithic constructions anywhere in the world.**

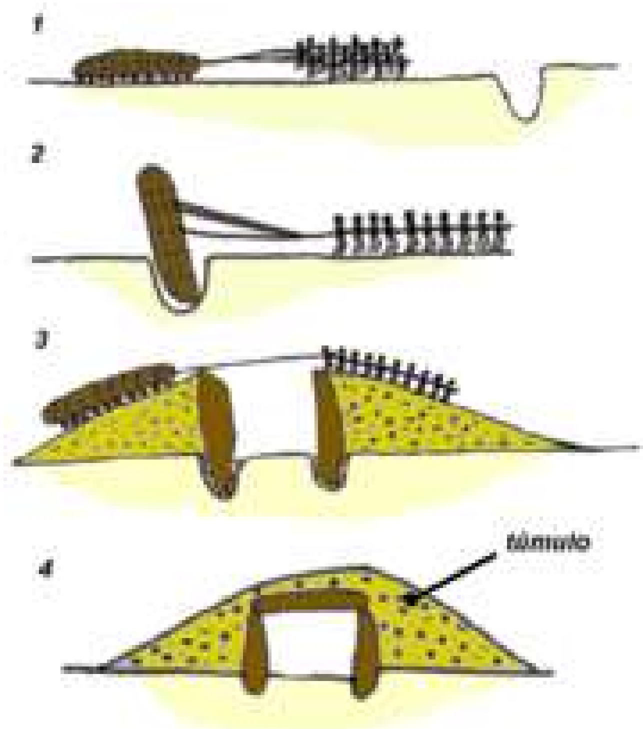


Figure 7.5: **Construction of a megalith grave.**

Figure 7.6: **Menhir of Goni in Sardinia. Ancient megalithic monuments are not confined to Europe. There are also many in Asia. Korea is estimated to have between 30,000 and 100,000 such monuments. One must also remember the megaliths on Easter Island. There are even megalithic cultures practicing today, for example in Indonesia.**

Figure 7.7: **Rano Raraku quarry on Easter Island.**

Figure 7.8: **Moai at Rano Raraku, Easter Island.**

Figure 7.9: **A megalithic monument in Korea.**

Figure 7.10: **Zorats Karer at Armenia (Armenian Stonehenge).**

Figure 7.11: **Megalithic dolmen in Marayoor, India.**

Figure 7.12: **Megalithic tomb in Khakasiya, Russian Federation.**

Figure 7.13: **Ale's Stones at Kåseberga, around ten kilometres south east of Ystad, Sweden.**

Figure 7.14: **Megaliths with engraved figures in Tiya, southern Ethiopia.**

Suggestions for further reading

1. Asthana, S. (1976). *History and archaeology of India's contacts with other countries, from earliest times to 300 B.C.*. Delhi: B.R. Pub. Corp.
2. Deo, S. B. (1973). *Problem of South Indian megaliths.* Dharwar: Kannada Research Institute, Karnatak University.
3. Goblet d'Alviella, E., & Wicksteed, P. H. (1892). *Lectures on the origin and growth of the conception of God as illustrated by anthropology and history.* London: Williams and Norgate.
4. Goudsward, D., & Stone, R. E. (2003). *America's Stonehenge: the . Boston: Branden Books. Illustrated Encyclopedia of Humankind (The): Worlds Apart* (1994) Weldon Owen Pty Limited
5. Keane, A. H. (1896). *Ethnology.* Cambridge: University Press.
6. Johnson, Walter (1908). *Folk-Memory: Or, The Continuity of British Archaeology.* Oxford: Clarendon Press.
7. Lancaster Brown, P. (1976). *Megaliths, myths, and men: an introduction to astro-archaeology.* New York: Taplinger Pub. Co.
8. Moffett, M., Fazio, M. W., & Wodehouse, L. (2004). *A world history of architecture.* Boston: McGraw-Hill.
9. Nelson, Sarah M. (1993) *The Archaeology of Korea.* Cambridge University Press, Cambridge.
10. O'Kelly, M. J., et al. (1989). *Early Ireland: An Introduction to Irish Prehistory.* Cambridge University Press.
11. Parker, Joanne (editor) (2009). *Written On Stone: The Cultural Reception of British Prehistoric Monuments* (Cambridge Scholars Publishing; 2009).
12. Patton, Mark (1993). *Statements in Stone: monuments and society in Neolithic Brittany.* Routledge. 209 pages.
13. Piccolo, Salvatore (2013). *Ancient Stones: The Prehistoric Dolmens of Sicily.* Thornham/Norfolk: Brazen Head Publishing.
14. Pohribný, Jan (photo) & Richards, J (introduction) (2007). *Magic Stones; the secret world of ancient megaliths.* London: Merrell.
15. Pozzi, Alberto (2013). *Megalithism - Sacred and Pagan Architecture in Prehistory.* Universal Publisher.
16. Scheltema, H.G. (2008). *Megalithic Jordan; an introduction and field guide.* Amman, Jordan: The American Center of Oriental Research.
17. Stukeley, W., Burl, A., & Mortimer, N. (2005). *Stukeley's 'Stonehenge': an unpublished manuscript, 1721-1724.* New Haven [Conn.]: Yale University Press.
18. Subbayya, K. K. (1978). *Archaeology of Coorg with special reference to megaliths.* Mysore: Geetha Book House.
19. Tyler, J. M. (1921). *The new stone age in northern Europe.* New York: C. Scribner's Sons.

20. Edwards, I. E. S., *The Pyramids of Egypt* Penguin Books Ltd; New edition (5 Dec 1991).
21. Lehner, Mark, *The Complete Pyramids*, Thames & Hudson, 1997.
22. Mendelssohn, Kurt, *The Riddle of the Pyramids*, Thames & Hudson Ltd (6 May 1974).
23. Arnold, H.J.P, *The Great Wall: Is It or Isn't It?* Astronomy Now, 1995.
24. Beckwith, Christopher I. (2009): *Empires of the Silk Road: A History of Central Eurasia from the Bronze Age to the Present.* Princeton: Princeton University Press.
25. Luo, Zewen, et al. and Baker, David, ed. (1981). *The Great Wall.* Maidenhead: McGraw-Hill Book Company (UK).
26. Man, John. (2008). *The Great Wall.* London: Bantam Press. 335 pages.
27. Michaud, Roland and Sabrina (photographers), & Michel Jan, *The Great Wall of China.* Abbeville Press, 2001.
28. Schafer, Edward H. (1985) *The Golden Peaches of Samarkand.* Berkeley: University of California Press.
29. Yamashita, Michael; Lindesay, William (2007). *The Great Wall - From Beginning to End.* New York: Sterling. 160 pages.
30. Joseph Needham, *Science and Civilization in China*, (4 volumes), Cambridge University Press (1954-1971).
31. Charles Singer, *A Short History of Scientific Ideas to 1900*, Oxford University Press (1959).
32. Ernst J. Grube, *The World of Islam*, Paul Hamlyn Ltd., London (1966).
33. Carl Brockelmann, *History of the Islamic Peoples*, Routledge and Kegan Paul (1949).
34. Marshall Clagett, *The Science of Mechanics in the Middle Ages*, The University of Wisconsin Press, Madison (1959).
35. lbanese, Marilia (2006). *The Treasures of Angkor* (Paperback). Vercelli: White Star Publishers. IS
36. Briggs, Lawrence Robert (1951, reprinted 1999). *The Ancient Khmer Empire.* White Lotus.
37. Forbes, Andrew; Henley, David (2011). *Angkor, Eighth Wonder of the World.* Chiang Mai: Cognoscenti Books.
38. Freeman, Michael and Jacques, Claude (1999). *Ancient Angkor.* River Books.
39. Higham, Charles (2001). *The Civilization of Angkor.* Phoenix.
40. Higham, Charles (2003). *Early Cultures of Mainland Southeast Asia.* Art Media Resources.
41. Hing Thoraxy. *Achievement of "APSARA": Problems and Resolutions in the Management of the Angkor Area.*
42. Jessup, Helen Ibbitson; Brukoff, Barry (2011). *Temples of Cambodia - The Heart of Angkor* (Hardback). Bangkok: River Books.
43. Petrotchenko, Michel (2011). *Focusing on the Angkor Temples: The Guidebook*, 383 pages, Amarin Printing and Publishing, 2nd edition.
44. Ray, Nick (2002). *Lonely Planet guide to Cambodia (4th edition).*

Chapter 8

THE INVENTION OF AGRICULTURE

8.1 Accelerating cultural evolution

An acceleration of human cultural development seems to have begun approximately 40,000 years ago. The first art objects date from that period, as do migrations which ultimately took modern man across the Bering Strait to the western hemisphere. A land bridge extending from Siberia to Alaska is thought to have been formed approximately 70,000 years ago, disappearing again roughly 10,000 years before the present. Cultural and genetic studies indicate that migrations from Asia to North America took place during this period. Shamanism,[1] which is found both in Asia and the new world, as well as among the Sami (Lapps) of northern Scandinavia, is an example of the cultural links between the hunting societies of these regions.

In the caves of Spain and southern France are the remains of vigorous hunting cultures which flourished between 30,000 and 10,000 years ago. The people of these upper Paleolithic cultures lived on the abundant cold-weather game which roamed the southern edge of the ice sheets during the Wurm glacial period: huge herds of reindeer, horses and wild cattle, as well as mammoths and wooly rhinos. The paintings found in the Dordogne region of France, for example, combine decorative and representational elements in a manner which contemporary artists might envy. Sometimes among the paintings are stylized symbols which can be thought of as the first steps towards writing.

In this period, not only painting, but also tool-making and weapon-making were highly developed arts. For example, the Solutrian culture, which flourished in Spain and southern France about 20,000 years ago, produced beautifully worked stone lance points in the shape of laurel leaves and willow leaves. The appeal of these exquisitely pressure-flaked blades must have been aesthetic as well as functional. The people of the Solutrian culture had

[1] A shaman is a special member of a hunting society who, while in a trance, is thought to be able to pass between the upper world, the present world, and the lower world, to cure illnesses, and to insure the success of a hunt.

Figure 8.1: **A cave painting showing a domesticated dog.**

fine bone needles with eyes, bone and ivory pendants, beads and bracelets, and long bone pins with notches for arranging the hair. They also had red, yellow and black pigments for painting their bodies. The Solutrian culture lasted for 4,000 years. It ended in about 17,000 B.C. when it was succeeded by the Magdalenian culture. Whether the Solutrian people were conquered by another migrating group of hunters, or whether they themselves developed the Magdalenian¡ culture we do not know.

Wikipedia states that "The dog diverged from a now-extinct population of wolves immediately before the Last Glacial Maximum, when much of Eurasia was a cold, dry mammoth steppe biome.... The archaeological record shows the first undisputed dog remains buried beside humans 14,700 years ago, with disputed remains occurring 36,000 years ago. These dates imply that the earliest dogs arose in the time of human hunter-gatherers and not agriculturalists. The dog was the first species to be domesticated."

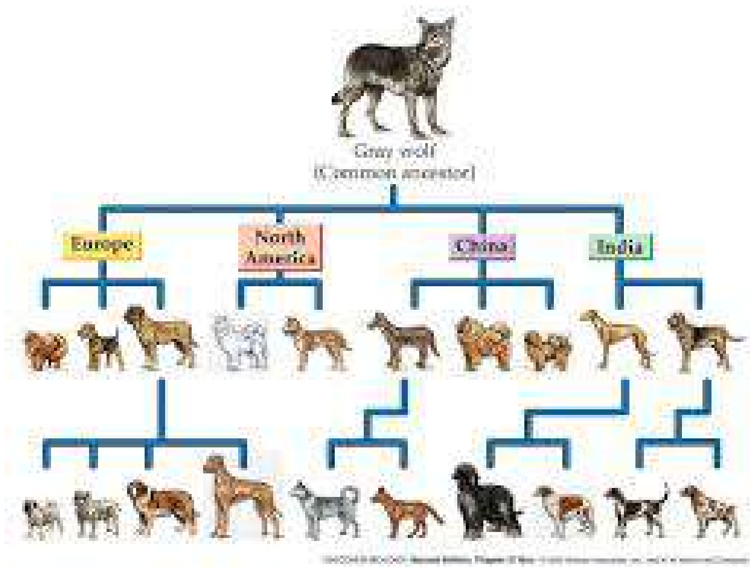


Figure 8.2: **The family tree of dogs, showing their descent from the grey wolf.**

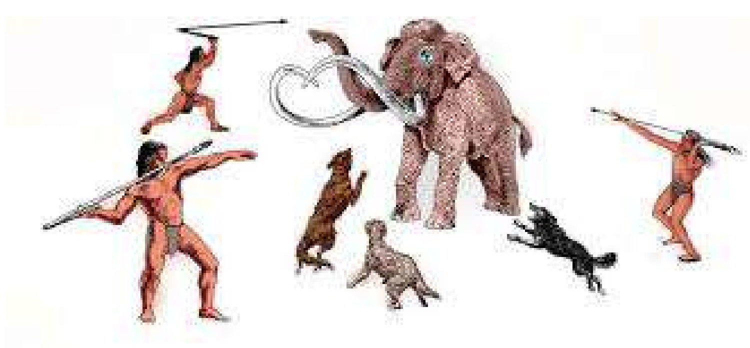


Figure 8.3: **Neolithic humans hunting a mammoth with the help of dogs.**

8.2 Early agriculture in the Middle East

Beginning about 10,000 B.C., the way of life of the hunters was swept aside by a great cultural revolution: the invention of agriculture. The earth had entered a period of unusual climatic stability, and this may have helped to make agriculture possible. The first agricultural villages date from this time, as well as the earliest examples of pottery. Dogs and reindeer were domesticated, and later, sheep and goats. Radio-carbon dating shows that by 8,500 B.C., people living in the caves of Shanidar in the foothills of the Zagros mountains in Iran had domesticated sheep. By 7,000 B.C., the village farming community at Jarmo in Iraq had domesticated goats, together with barley and two different kinds of wheat.

Starting about 8000 B.C., rice came under cultivation in East Asia. This may represent an independent invention of agriculture, and agriculture may also have been invented independently in the western hemisphere, made possible by the earth's unusually stable climate during this period. At Jericho, in the Dead Sea valley, excavations have revealed a prepottery neolithic settlement surrounded by an impressive stone wall, six feet wide and twelve feet high. Radiocarbon dating shows that the defenses of the town were built about 7,000 B.C. Probably they represent the attempts of a settled agricultural people to defend themselves from the plundering raids of less advanced nomadic tribes.

Starting in western Asia, the neolithic agricultural revolution swept westward into Europe, and eastward into the regions that are now Iran and India. By 4,300 B.C., the agricultural revolution had spread southwest to the Nile valley, where excavations along the shore of Lake Fayum have revealed the remains of grain bins and silos. The Nile carried farming and stock-breeding techniques slowly southward, and wherever they arrived, they swept away the hunting and food-gathering cultures. By 3,200 B.C. the agricultural revolution had reached the Hyrax Hill site in Kenya. At this point the southward movement of agriculture was stopped by the swamps at the headwaters of the Nile. Meanwhile, the Mediterranean Sea and the Danube carried the revolution westward into Europe. Between 4,500 and 2,000 B.C. it spread across Europe as far as the British Isles and Scandinavia.

However, western Asia was only one of the places where the agricultural revolution took place. Wikipedia states that “ Agriculture began independently in different parts of the globe, and included a diverse range of taxa. At least eleven separate regions of the Old and New World were involved as independent centers of origin.

“Wild grains were collected and eaten from at least 20,000 BC. From around 9,500 BC, the eight Neolithic founder crops - emmer wheat, einkorn wheat, hulled barley, peas, lentils, bitter vetch, chick peas, and flax - were cultivated in the Levant. Rice was domesticated in China between 11,500 and 6,200 BC, followed by mung, soy and azuki beans. Pigs were domesticated in Mesopotamia around 11,000 BC, followed by sheep between 11,000 and 9,000 BC. Cattle were domesticated from the wild aurochs in the areas of modern Turkey and Pakistan around 8,500 BC. Sugarcane and some root vegetables were domesticated in New Guinea around 7,000 BC. Sorghum was domesticated in the Sahel region of Africa by 5,000 BC. In the Andes of South America, the potato was domesticated between 8,000 and 5,000 BC, along with beans, coca, llamas, alpacas, and guinea pigs. Bananas were

Figure 8.4: **Early agriculture in Egypt: Threshing**

cultivated and hybridized in the same period in Papua New Guinea. In Mesoamerica, wild teosinte was domesticated to maize by 4,000 BC. Cotton was domesticated in Peru by 3,600 BC. Camels were domesticated late, perhaps around 3,000 BC."

Figure 8.5: **Pigs were domesticated in Mesopotamia around 11,000 BC.**

Figure 8.6: **Domestication of sheep.**

8.3 Rice cultivation in Asia

Wikipedia states that "Excavations at Kuahuqiao, the earliest known Neolithic site in eastern China, have documented rice cultivation 7,700 years ago. Approximately half of the plant remains belonged to domesticated japonica species, whilst the other half were wild types of rice. It is possible that the people at Kuahuqiao also cultivated the wild type. Finds at sites of the Hemudu Culture (c.5500-3300 BCE) in Yuyao and Banpo near Xi'an include millet and spade-like tools made of stone and bone. Evidence of settled rice agriculture has been found at the Hemudu site of Tianluoshan (5000-4500 BCE), with rice becoming the backbone of the agricultural economy by the Majiabang culture in southern China."

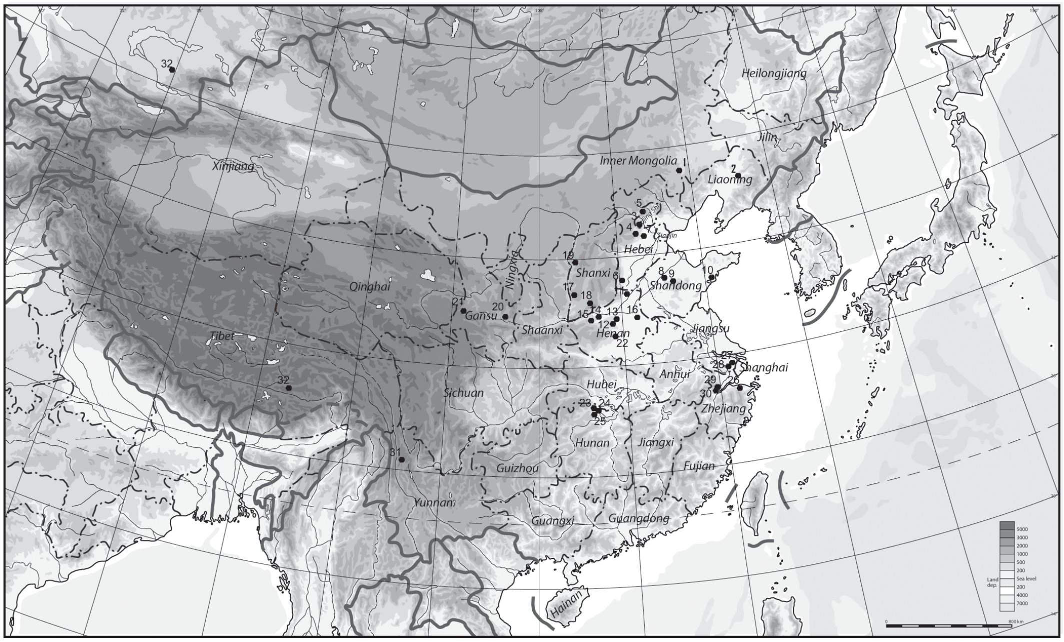


Figure 8.7: **A map showing sites of early rice-growing in China.**

Figure 8.8: **Ancient rice terraces in Yuanyang, Yunnan, a province in southern China.**

8.4 Agriculture in the western hemisphere

During a glacial period between 20,000 and 10,000 years before the present, there was a land bridge across the Bering Strait. There is evidence that humans crossed this land bridge from Siberia and followed a coastal route past the glaciated regions of what is now Canada, finally reaching South America. Humans were able to build boats at that time, as evidenced by traces of very early settlements on islands off the coast of South America.

A site that shows evidence of early human presence is Piki Mach'ay cave in Peru Radiocarbon dates from this cave give a human presence ranging from 22,200 to 14,700 years ago, but this evidence has been disputed. Wikipedia states that "Piki Mach'ay yielded some of the oldest plant remains in Peru, including an 11,000 year old bottle gourd. Strata from later periods at the site revealed fishtail points, manos, and metates. Plant remains indicate that, before 3,000 years BCE, amaranth, cotton, gourds, lucuma, quinoa, and squash were cultivated in the Ayacucho Basin before 3,000 years BCE. By 4,000 years BCE corn (Zea mays) and common beans were grown. Chili remains date from 5,500 to 4,300 years BCE. The large amounts of guinea pig bones suggest possible domestication, and llamas may have been domesticated by 4,300 to 2,800 years BCE."

Figure 8.9: **The “three sisters”, maize, squash and beans, traditionally grown by tribes of the first people in North America.**

Figure 8.10: **An artist’s guess at what the inhabitants of Piki Mach’ay cave in Peru might have looked like.**

8.5 Peru gives potatoes to the world

Wikipedia states that **"Cultivation of potatoes in South America may go back 10,000 years, yet the tubers do not preserve well in archaeological record, and there are problems with exact identification of those that are found... In the Altiplano, potatoes provided the principal energy source for the Inca Empire, its predecessors, and its Spanish successor... Potato was the staple food of most Pre-Columbian Mapuches[2], 'specially in the southern and coastal [Mapuche] territories where maize did not reach maturity"**

[2]The Mapuche are a group of indigenous inhabitants of south-central Chile and southwestern Argentina, including parts of present-day Patagonia.

Figure 8.11: **In the mountainous regions of Peru, the ancient Incas built terraces for the cultivation of potatoes.**

Suggestions for further reading

1. P. Dasgupta, *Population, Resources and Poverty*, Ambio, **21**, 95-101, (1992).
2. L.R. Brown, *Who Will Feed China?*, W.W. Norton, New York, (1995).
3. L.R. Brown, et al., *Saving the Planet. How to Shape and Environmentally Sustainable Global Economy*, W.W. Norton, New York, (1991).
4. L.R. Brown, *Postmodern Malthus: Are There Too Many of Us to Survive?*, The Washington Post, July 18, (1993).
5. L.R. Brown and H. Kane, *Full House. Reassessing the Earth's Population Carrying Capacity*, W.W. Norton, New York, (1991).
6. L.R. Brown, *Seeds of Change*, Praeger Publishers, New York, (1970).
7. L.R. Brown, *The Worldwide Loss of Cropland*, Worldwatch Paper 24, Worldwatch Institute, Washington, D.C., (1978).
8. L.R. Brown, and J.L. Jacobson, *Our Demographically Divided World*, Worldwatch Paper 74, Worldwatch Institute, Washington D.C., (1986).
9. L.R. Brown, and J.L. Jacobson, *The Future of Urbanization: Facing the Ecological and Economic Constraints*, Worldwatch Paper 77, Worldwatch Institute, Washington D.C., (1987).
10. L.R. Brown, and others, *State of the World*, W.W. Norton, New York, (published annually).
11. H. Brown, *The Human Future Revisited. The World Predicament and Possible Solutions*, W.W. Norton, New York, (1978).

12. H. Hanson, N.E. Borlaug and N.E. Anderson, *Wheat in the Third World*, Westview Press, Boulder, Colorado, (1982).
13. A. Dil, ed., *Norman Borlaug and World Hunger*, Bookservice International, San Diego/Islamabad/Lahore, (1997).
14. N.E. Borlaug, *The Green Revolution Revisitied and the Road Ahead*, Norwegian Nobel Institute, Oslo, Norway, (2000).
15. N.E. Borlaug, *Ending World Hunger. The Promise of Biotechnology and the Threat of Antiscience Zealotry*, Plant Physiology, **124**, 487-490, (2000).
16. M. Giampietro and D. Pimental, *The Tightening Conflict: Population, Energy Use and the Ecology of Agriculture*, in *Negative Population Forum*, L. Grant ed., Negative Population Growth, Inc., Teaneck, N.J., (1993).
17. H.W. Kendall and D. Pimental, *Constraints on the Expansion of the Global Food Supply*, Ambio, **23**, 198-2005, (1994).
18. D. Pimental et al., *Natural Resources and Optimum Human Population*, Population and Environment, **15**, 347-369, (1994).
19. D. Pimental et al., *Environmental and Economic Costs of Soil Erosion and Conservation Benefits*, Science, **267**, 1117-1123, (1995).
20. D. Pimental et al., *Natural Resources and Optimum Human Population*, Population and Environment, **15**, 347-369, (1994).
21. D. Pimental and M. Pimental, *Food Energy and Society*, University Press of Colorado, Niwot, Colorado, (1996).
22. D. Pimental et al., *Environmental and Economic Costs of Soil Erosion and Conservation Benefits*, Science, **267**, 1117-1123, (1995).
23. RS and NAS, *The Royal Society and the National Academy of Sciences on Population Growth and Sustainability*, Population and Development Review, **18**, 375-378, (1992).
24. A.M. Altieri, *Agroecology: The Science of Sustainable Agriculture*, Westview Press, Boulder, Colorado, (1995).
25. G. Conway, *The Doubly Green Revolution*, Cornell University Press, (1997).
26. J. Dreze and A. Sen, *Hunger and Public Action*, Oxford University Press, (1991).
27. G. Bridger, and M. de Soissons, *Famine in Retreat?*, Dent, London, (1970).
28. W. Brandt, *World Armament and World Hunger: A Call for Action*, Victor Gollanz Ltd., London, (1982).
29. A.K.M.A. Chowdhury and L.C. Chen, *The Dynamics of Contemporary Famine*, Ford Foundation, Dacca, Pakistan, (1977)
30. J. Shepard, *The Politics of Starvation*, Carnegie Endowment for International Peace, Washington D.C., (1975).
31. M.E. Clark, *Ariadne's Thread: The Search for New Modes of Thinking*, St. Martin's Press, New York, (1989).
32. J.-C. Chesnais, *The Demographic Transition*, Oxford, (1992).
33. C.M. Cipola, *The Economic History of World Population*, Penguin Books Ltd., (1974).
34. E. Draper, *Birth Control in the Modern World*, Penguin Books, Ltd., (1972).

35. Draper Fund Report No. 15, *Towards Smaller Families: The Crucial Role of the Private Sector*, Population Crisis Committee, 1120 Nineteenth Street, N.W., Washington D.C. 20036, (1986).
36. E. Eckholm, *Losing Ground: Environmental Stress and World Food Prospects*, W.W. Norton, New York, (1975).
37. E. Havemann, *Birth Control*, Time-Life Books, (1967).
38. J. Jacobsen, *Promoting Population Stabilization: Incentives for Small Families*, Worldwatch Paper 54, Worldwatch Institute, Washington D.C., (1983).
39. N. Keyfitz, *Applied Mathematical Demography*, Wiley, New York, (1977).
40. W. Latz (ed.), *Future Demographic Trends*, Academic Press, New York, (1979).
41. World Bank, *Poverty and Hunger: Issues and Options for Food Security in Developing Countries*, Washington D.C., (1986).
42. J.E. Cohen, *How Many People Can the Earth Support?*, W.W. Norton, New York, (1995).
43. J. Amos, *Climate Food Crisis to Deepen*, BBC News (5 September, 2005).
44. J. Vidal and T. Ratford, *One in Six Countries Facing Food Shortage*, The Guardian, (30 June, 2005).
45. J. Mann, *Biting the Environment that Feeds Us*, The Washington Post, July 29, 1994.
46. G.R. Lucas, Jr., and T.W. Ogletree, (editors), *Lifeboat Ethics. The Moral Dilemmas of World Hunger*, Harper and Row, New York.
47. J.L. Jacobson, *Gender Bias: Roadblock to Sustainable Development*, Worldwatch Paper 110, Worldwatch Institute, Washington D.C., (1992).
48. J. Gever, R. Kaufmann, D. Skole and C. Vorosmarty, *Beyond Oil: The Threat to Food and Fuel in the Coming Decades*, Ballinger, Cambridge MA, (1986).
49. M. ul Haq, *The Poverty Curtain: Choices for the Third World*, Columbia University Pres, New York, (1976).
50. H. Le Bras, *La Planète au Village*, Datar, Paris, (1993).
51. E. Mayr, *Population, Species and Evolution*, Harvard University Press, Cambridge, (1970).
52. Food and Agriculture Organization (FAO), *The Global Forest Assessment 2000* (Rome: Food and Agriculture Organization, Committee on Forestry, 2000).
53. Thomas K. Rudel, Kevin Flesher, Diana Bates, Sandra Baptista, and Peter Holmgren, *Tropical Deforestation Literature: Geographical and Historical Patterns*, Unasylva **203**, Vol. 51 (2000): 11-18;
54. Alexander S. Pfaff, *What drives deforestation in the Brazilian Amazon?* Journal of Economics and Management **37** (1999): 26-43.
55. Phillip M. Fearnside, *Human Carrying Capacity Estimation in Brazilian Amazonia as the Basis for Sustainable Development,* Environmental Conservation **24** (1997): 271-82;
56. Frederick A.B. Meyerson, *Human Population Density, Deforestation and Protected Areas Management: A Multi-scale Analysis of Central America, Guatemala,*

57. The Maya Biosphere Reserve, *Proceedings of the International Union for the Scientific Study of Population*, XXIV General Population Conference (Salvador, Brazil, 2001).
58. C.H. Wood and David L. Skole, *Linking satellite, census, and survey data to study deforestation in the Brazilian Amazon,* in *People and Pixels*, ed. D. Liverman et al. (Washington, DC: National Academies Press, 1998).
59. Suzi Kerr, Alexander S. Pfaff, and Arturo Sanchez, *Development and Deforestation: Evidence From Costa Rica* (unpublished paper, 2003).
60. Frederick A.B. Meyerson, *Population, Biodiversity and Changing Climate*, Advances in Applied Biodiversity Science **4** (2003), Chapter 11 (2003): 83-90
61. Andrew D. Foster and Mark R. Rosenzweig, *Economic Growth and the Rise of Forests*," The Quarterly Journal of Economics (May 2003): 601-637.
62. A. Balmford et al., *Conservation Conflicts Across Africa*, Science **291** (2001): 2616-19.
63. Richard P. Cincotta, Jennifer Wisnewski, and Robert Engelman, *Human Population in the Biodiversity Hotspots*, Nature **404** (2000): 990-92.
64. Food and Agriculture Organization of the United Nations (FAO). 2010. *Global Forest Resources Assessment 2010.* Rome: FAO.
65. World Bank. 2004. *Sustaining Forests: A Development Strategy.* Washington DC: World Bank.
66. Food and Agriculture Organization of the United Nations (FAO). 2006. *Global Forest Resources Assessment 2005: Progress Towards Sustainable Forest Management.* Rome: FAO.
67. United Nations Population Division. 2009. *World Population Prospects: The 2008 Revision.* New York: UN Population Division.
68. Pan, W, D Carr, A Barbierri, R Bilsborrow and C Suchindran. 2007. *Forest Clearing in the Ecuadorian Amazon: A Study of Patterns Over Space and Time.* Population Research and Policy Review **26**:635-659.
69. Geist, H J and E F Lambin. 2002. *Proximate Causes and Underlying Driving Forces of Tropical Deforestation.* Bioscience **52(2)**: 143-150.
70. Rosero-Bixby, L and A Palloni. 1996. *Population and Deforestation in Costa Rica.* CDE Working Paper No. 96-19. Madison: 1996.
71. Carr, D, L Sutter and A Barbieri. 2006. *Population Dynamics and Tropical Deforestation: State of the Debate and Conceptual Challenges.* Population and Environment **27**:89-113.
72. Barreto, P, C Souza, R Nogueron, A Anderson, R Salamao and J Wiles. 2006. *Human Pressure on the Brazilian Amazon Forests.* Washington DC: World Resources Institute (WRI).
73. Ramankutty, N, JA Foley and NJ Olejniczak. 2002. *People on the Land: Changes in Global Population and Croplands during the 20th Century.* Ambio **31(3)**: 251-257.
74. Food and Agriculture Organization of the United Nations (FAO). 2008. *Forests and Energy: Key Issues.* Rome: FAO.

75. Millenium Ecosytem Assessment. 2005. *Ecosystems and Human Well-Being Biodiversity Synthesis.* Washington DC: World Resources Institute (WRI).
76. Sherbinin, A, D Carr, S Cassels and L Jiang. 2007. *Population and Environment.* The Annual Review of Environment and Resources **32**: 345-373.
77. Leahy, E, R Englelman, C Vogel, S Haddock and T Preston. 2007. **The Shape of Things to Come.** Washington, DC: PAI.
78. DeFries, R, T K Rudel, M Uriarte and M Hansen. 2010. *Deforestation Driven by Urban Population Growth and Agricultural Trade in the Twenty-First Century.* Nature Geoscience **3**: 178-181.
79. Lambin, E F and P Meyfroidt. 2011. *Global Land Use Change, Economic Globalization, and the Looming Land Scarcity.* Proceedings of the National Academy of Sciences **108**: 3465-3472.
80. United Nations Population Division. 2010. *World Urbanization Prospects: The 2009 Revision.* New York: UN Population Division.
81. Bonan, G. B. (2008). *Forests and climate change: Forcings, feedbacks, and the climate benefits of forests.* Science. **320** (5882): 1444-1449.
82. Scheil, D.; Murdiyarso, D. (2009). *How Forests Attract Rain: An Examination of a New Hypothesis.* BioScience. **59** (4): 341-347.
83. Ahmad, Y.J. and M. Kassas. 1987. *Desertification: Financial Support for the Biosphere.* West Hartford, Conn.: Kumarian Press.
84. Barrow, C. J. 1991. *Land Degradation - Developments and Breakdown of Terrestrial Environments.* Cambridge: Cambridge University Press.
85. Gadgil, M. 1989. *Deforestation: Problems and prospects.* Foundation Day Lecture, Society for Promotion of Wastelands Development, 12 May, New Delhi. Centre of Ecological Sciences and Theoretical Studies, Indian Institute of Science Bangalore.
86. Government of India. 1987. *State of Forest Report 1987.* Forest Survey of India, Dehradun.
87. Government of India. 1991. *State of Forest Report, 1987-1989.* Forest Survey of India, Dehradun.
88. Kassas, M. 1987. *Drought and desertification.* Land Use Policy **4(4)**: 389-400.
89. Kemp, D. D. 1990. *Global Environmental Issues - A Climatological Approach.* London: Routledge.
90. Maheshwari, J. K. 1989. *Processing and Utilization of Perennial Vegetation in the Arid Zone of India* in **Role of Forestry in Combatting Desertification.** Rome: FAO Conservation Guide 21, pp. 137-172.
91. Reining, P. 1978. *Handbook on Desertification Indicators.* Washington, D.C.: American Association for the Advancement of Science.
92. Tolba, M. K. 1987. *Sustainable Development: Constraints and Opportunities* London: Butterworth.
93. Tolba, M. K., O. A. El-Kholy, et al. 1992. *The World Environment 1972-1992. Two Decades of Challenge.* London: Chapman and Hall.
94. Tucker, C. J., H. E. Dregne, and W. W. Newcomb. 1991. *Expansion and contraction of Sahara Desert from 1980-1990.* Science **253**.

95. UNCED (United Nations Conference on Environment and Development). 1992. *Agenda 21.* United Nations Conference on Environment and Development, Brazil, June 3-14,1992. Brazil: UNCED.
96. UNEP (United Nations Environment Programme). 1984. *General Assessment of Progress in the Implementation of the Plan of Action to Combat Desertification, 1978-1984.* GC-12/9.
97. UNEP (United Nations Environment Programme). 1991. *Status of Desertification and Implementation of the United Nations Plan of Action to Control Desertification.* Nairobi: UNEP.
98. Winpenny, J. T. (ed.). 1990. *Development Research: The Environmental Challenge.* Boulder, Colo.: Westview Press, for the ODI.
99. Wood, W. B. 1990. *Tropical Deforestation. Balancing Regional Development Demands and Global Environmental Concerns.*
100. World Bank. 1989. *World Development Report 1989.* Oxford: Oxford University Press.
101. World Bank. 1992. *World Development Report 1992.* Oxford: Oxford University Press.

Chapter 9

THE INVENTION OF WRITING

9.1 Mesopotamia

In Mesopotamia (which in Greek means "between the rivers"), the settled agricultural people of the Tigris and Euphrates valleys evolved a form of writing. Among the earliest Mesopotamian writings are a set of clay tablets found at Tepe Yahya in southern Iran, the site of an ancient Elamite trading community halfway between Mesopotamia and India.

The Elamite trade supplied the Sumarian civilization of Mesopotamia with silver, copper, tin, lead, precious gems, horses, timber, obsidian, alabaster and soapstone. The practical Sumerians and Elamites probably invented writing as a means of keeping accounts.

The tablets found at Tepe Yahya are inscribed in proto-Elamite, and radio-carbon dating of organic remains associated with the tablets shows them to be from about 3,600 B.C.. The inscriptions on these tablets were made by pressing the blunt and sharp ends of a stylus into soft clay. Similar tablets have been found at the Sumerian city of Susa at the head of the Tigris River.

In about 3,100 B.C. the cuneiform script was developed, and later Mesopotamian tablets are written in cuneiform, which is a phonetic script where the symbols stand for syllables.

Figure 9.1: **Sumerian writing**

9.2 Egypt

The Egyptian hieroglyphic (priest writing) system began its development in about 4,000 B.C.. At that time, it was pictorial rather than phonetic. However, the Egyptians were in contact with the Sumerian civilization of Mesopotamia, and when the Sumerians developed a phonetic system of writing in about 3,100 B.C., the Egyptians were quick to adopt the idea. In the cuneiform writing of the Sumerians, a character stood for a syllable. In the Egyptian adaptation of this idea, most of the symbols stood for combinations of two consonants, and there were no symbols for vowels. However, a few symbols were purely alphabetic, i.e. they stood for sounds which we would now represent by a single letter. This was important from the standpoint of cultural history, since it suggested to the Phoenicians the idea of an alphabet of the modern type.

In Sumer, the pictorial quality of the symbols was lost at a very early stage, so that in the cuneiform script the symbols are completely abstract. By contrast, the Egyptian system of writing was designed to decorate monuments and to be impressive even to an illiterate viewer; and this purpose was best served by retaining the elaborate pictographic form of the symbols.

Figure 9.2: **The Phoenician alphabet**

Figure 9.3: **Hieroglyphics, or "priest writing", was designed to be impressive even to the illiterate viewer**

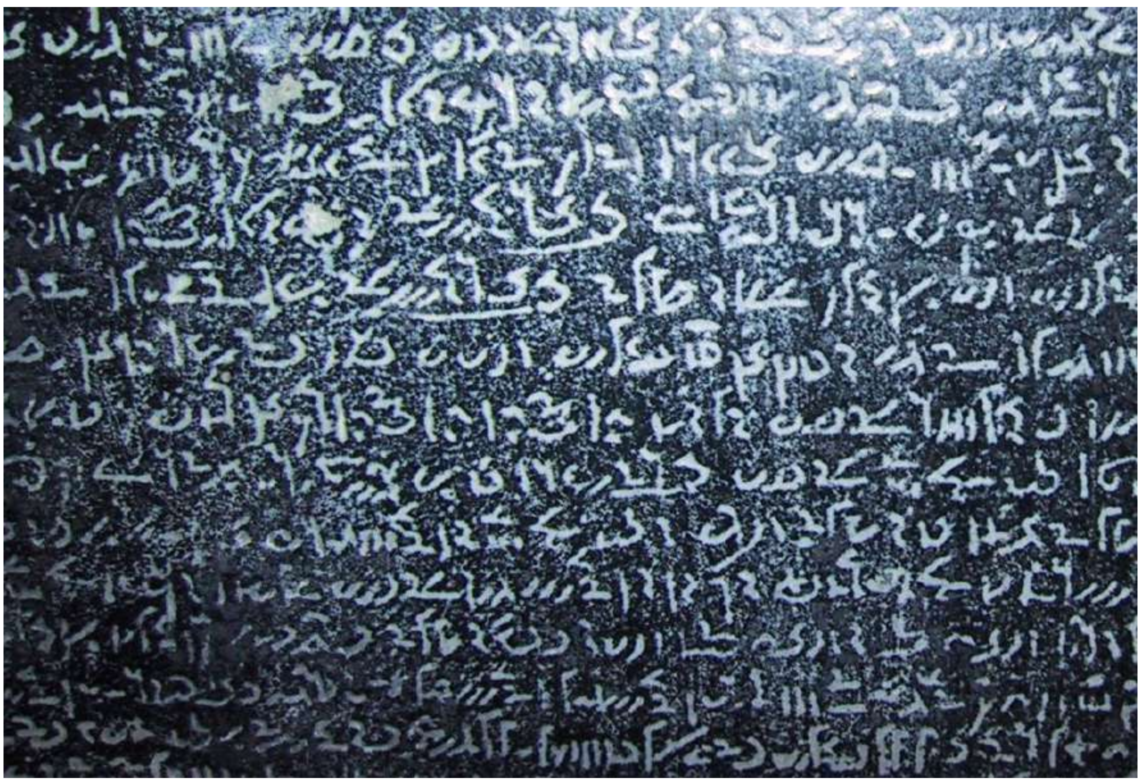


Figure 9.4: **Demotic writing was used by the ordinary people of ancient Egypt**

9.3 China

Writing was developed at a very early stage in Chinese history, but the system remained a pictographic system, with a different character for each word. A phonetic system of writing was never developed.

The failure to develop a phonetic system of writing had its roots in the Chinese imperial system of government. The Chinese empire formed a vast area in which many different languages were spoken. It was necessary to have a universal language of some kind in order to govern such an empire. The Chinese written language solved this problem admirably.

Suppose that the emperor sent identical letters to two officials in different districts. Reading the letters aloud, the officials might use entirely different words, although the characters in the letters were the same. Thus the Chinese written language was a sort of "Esperanto" which allowed communication between various language groups, and its usefulness as such prevented its replacement by a phonetic system.

The disadvantages of the Chinese system of writing were twofold: First, it was difficult to learn to read and write; and therefore literacy was confined to a small social class whose members could afford a prolonged education. The system of civil-service examinations made participation in the government dependant on a high degree of literacy; and hence the old, established scholar-gentry families maintained a long-term monopoly on power, wealth and education. Social mobility was possible in theory, since the civil service examinations were open to all, but in practice, it was nearly unattainable.

The second great disadvantage of the Chinese system of writing was that it was unsuitable for printing with movable type. An "information explosion" occurred in the west following the introduction of printing with movable type, but this never occurred in China. It is ironical that although both paper and printing were invented by the Chinese, the full effect of these immensely important inventions bypassed China and instead revolutionized the west.

Figure 9.5: **Very early Chinese writing on a bone**

Figure 9.6: **Chinese writing in a later form**

9.4 Europe

Figure 9.7: **Runic writing system used in Scandinavia**

Figure 9.8: **The writing of the pre-Roman Etruscan civilization**

Figure 9.9: **Linear B, used by the Mycenaean civilization, preceded the Greek alphabet by several centuries**

9.5 The Americas

The Mayan system of writing is thought to have been invented in about 700 B.C., and this invention is believed to be entirely independent of the invention of writing elsewhere. Some of the Mayan glyphs represented entire words, but the could also represent syllables.

Knotted string systems of keeping records were used by the Andean peoples of South America, especially by the Inca civilization. In the Incan language collections of knotted strings were known as *quipus* or talking knots. Quipus could have only a few, or as many as 2000 knotted strings.

Belts made from shell beads (*wampum*) were used by the natives peoples of North America, both as currency and as a means of recording events.

Figure 9.10: **Knotted strings (Quipu) in the Museo Machu Picchu, Casa Concha, Cusco.**

Figure 9.11: **Mayan writing.**

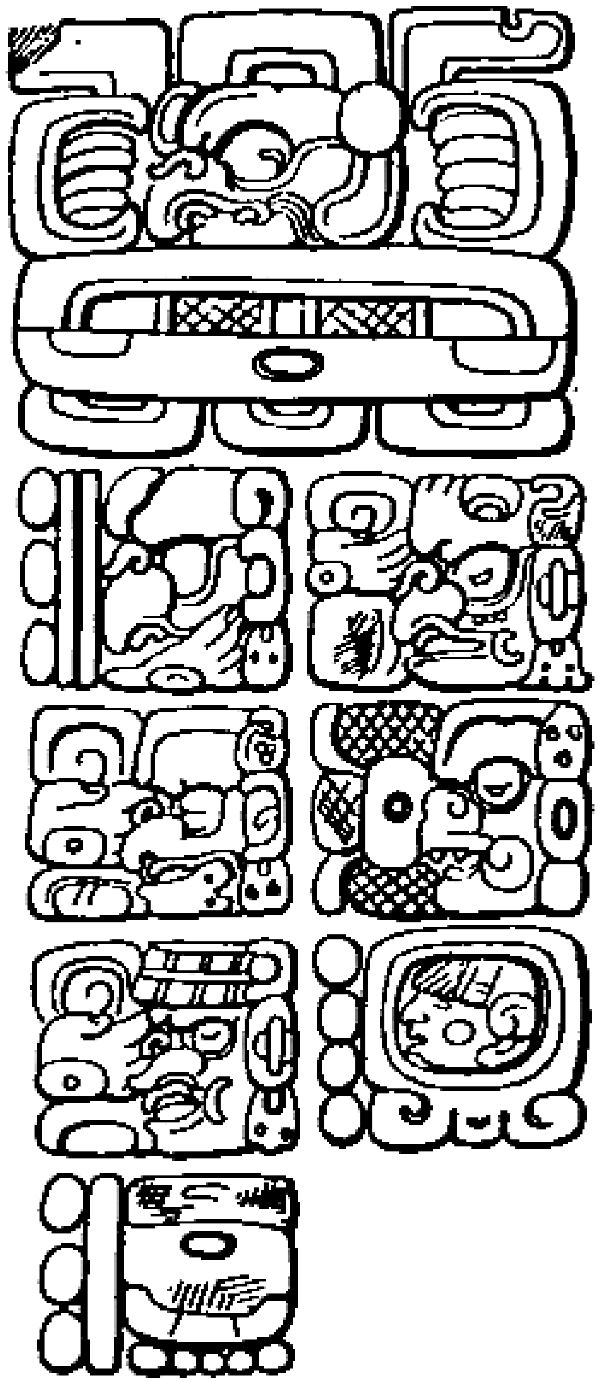


Figure 9.12: **East side of stela C, Quirigua with the mythical creation date. of 13 baktuns, 0 katuns, 0 tuns, 0 uinals, 0 kins, 4 Ahau 8 Cumku - August 11, 3114 BCE in the proleptic Gregorian calendar.**

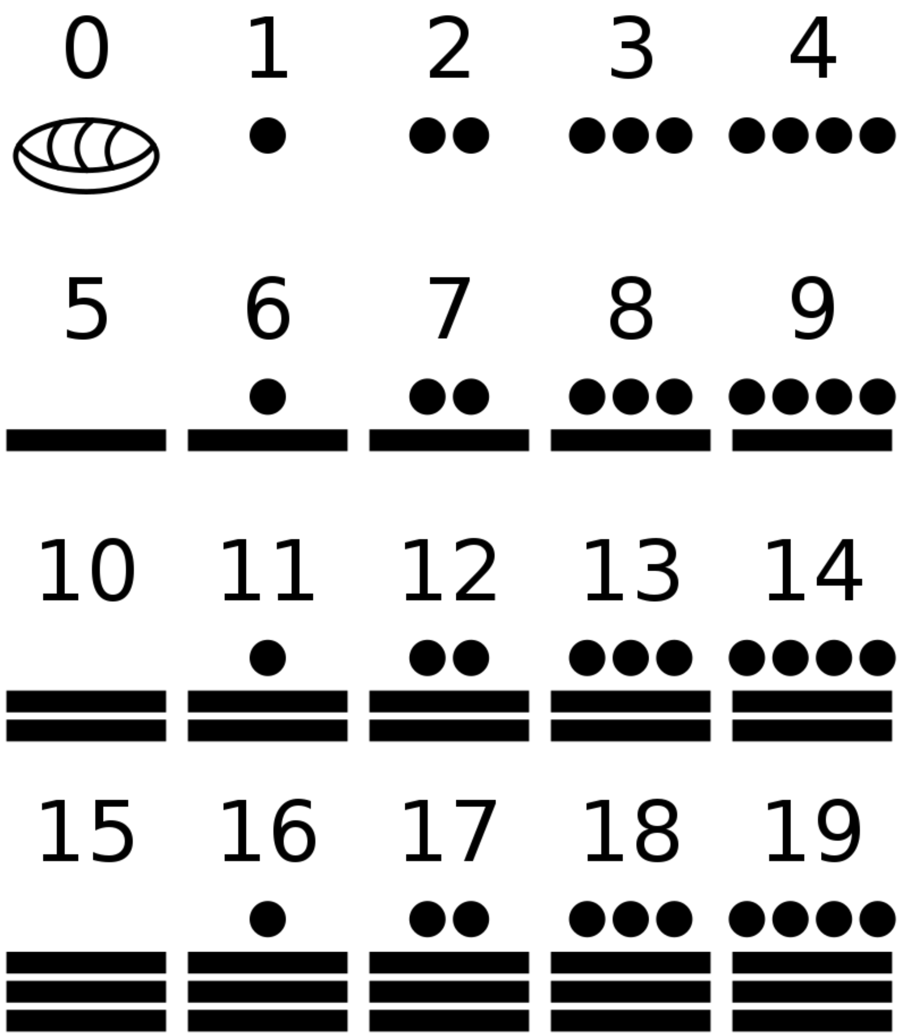


Figure 9.13: **Mayan numerals.**

Appendix A

EARLY HISTORY OF THE EARTH

A.1 Formation of the Sun and the Earth

Our local star, the Sun, was formed from molecular clouds in interstellar space, which had been produced by the explosion of earlier stars. Our Sun contains mainly hydrogen and a little helium, with very small amounts of heavier elements. The vast amounts of energy produced by the sun come mainly from a nuclear reaction in which hydrogen is converted into helium.

There were clouds of containing not only hydrogen and helium, but also heavier elements left swirling around the infant Sun. Gradually, over many millions of years, these condensed through a process of collision and accretion, to form the planets. In the four relatively small inner planets, Mercury, Venus, Earth and Mars, heavy elements predominate, while in the giants, Jupiter, Saturn, Uranus and Neptune, we find lighter elements.

The Sun accounts for 99.86% of the solar system's mass, while the four giant planets contain 99% of the remaining mass.

One *astronomical unit* (1 AU) is, by definition, the average distance of the earth from the sun, i.e. approximately 93 million miles or 150 million kilometers. In terms of this unit, the average distances of the planets from the sun are as follows: Mercury, 0.387 AU; Venus, 0.722 AU; Earth, 1.000 AU; Mars, 1.52 AU; Jupiter, 5.20 AU; Saturn, 9.58 AU; Uranus, 19.2 AU; Neptune, 30.1 AU.

The Solar System also includes the asteroid belt, which lies between the orbits of Mars and Jupiter; the Kuiper belt and scattered disc, which are populations of trans-Neptunian objects; the dwarf planets, Ceres, Pluto and Eris; and the comets. Many of the bodies in the solar system, including six of the planets, have natural satellites or moons. The Earth's moon was produced by collision with a Mars-sized body, soon after the formation of the Earth.

Of the four inner planets, the Earth is the only one that has large amounts of liquid water on its surface. When the Earth cooled sufficiently after the violent collision that gave us our Moon, oceans began to form, and life is believed to have originated in the oceans, approximately 3.8 billion years before the present.

Figure A.1: **Much experimental evidence supports the Standard Model of cosmology, according to which our Universe began in an enormously hot and dense state 15.8 billion years ago, from which it is exploding outward. By 10 billion years before the present it had cooled enough for the first stars to form. Our own local star, the Sun, was formed 4.54 billion years ago from dust clouds left when earlier stars exploded. These dust clouds contained not only large amounts of hydrogen and a little helium, but also small amounts of the heavy elements that are needed for life. These heavy elements had been produced by nuclear reactions in the core regions of earlier stars.**

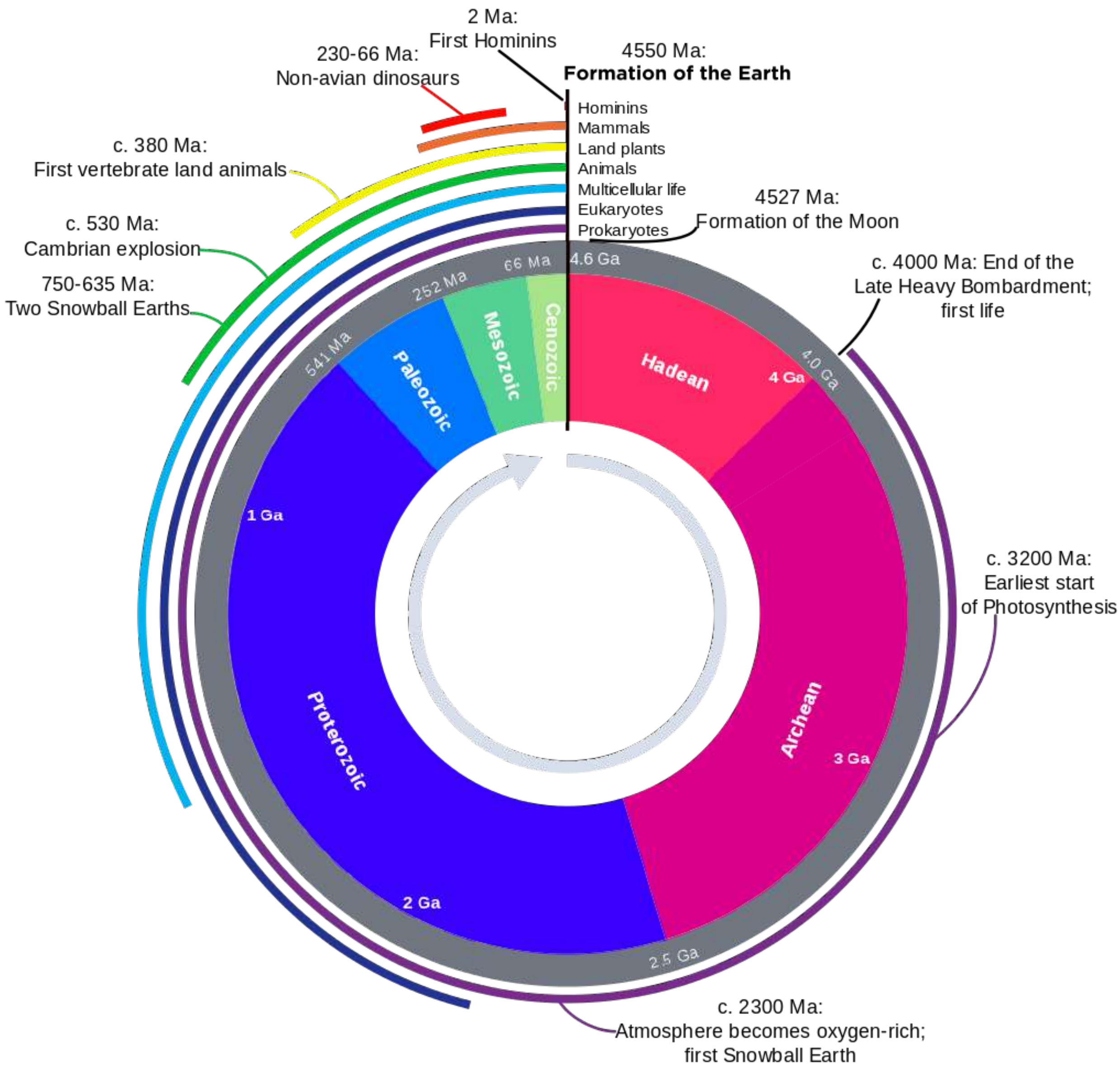


Figure A.2: **Geologic time represented in a diagram called a geological clock, showing the relative lengths of the eons of Earth's history and noting major events. During the Hadian eon, the earth was extremely hot, because of its recent accretion, the abundance of short-lived radioactive elements, and frequent collisions with other Solar System bodies. The word Hadian is derived from the name of the Greek god of the underworld, and it is used to describe the hellish conditions on the early earth. On the time-scale of this geological clock, humans appeared at the very last moment.**

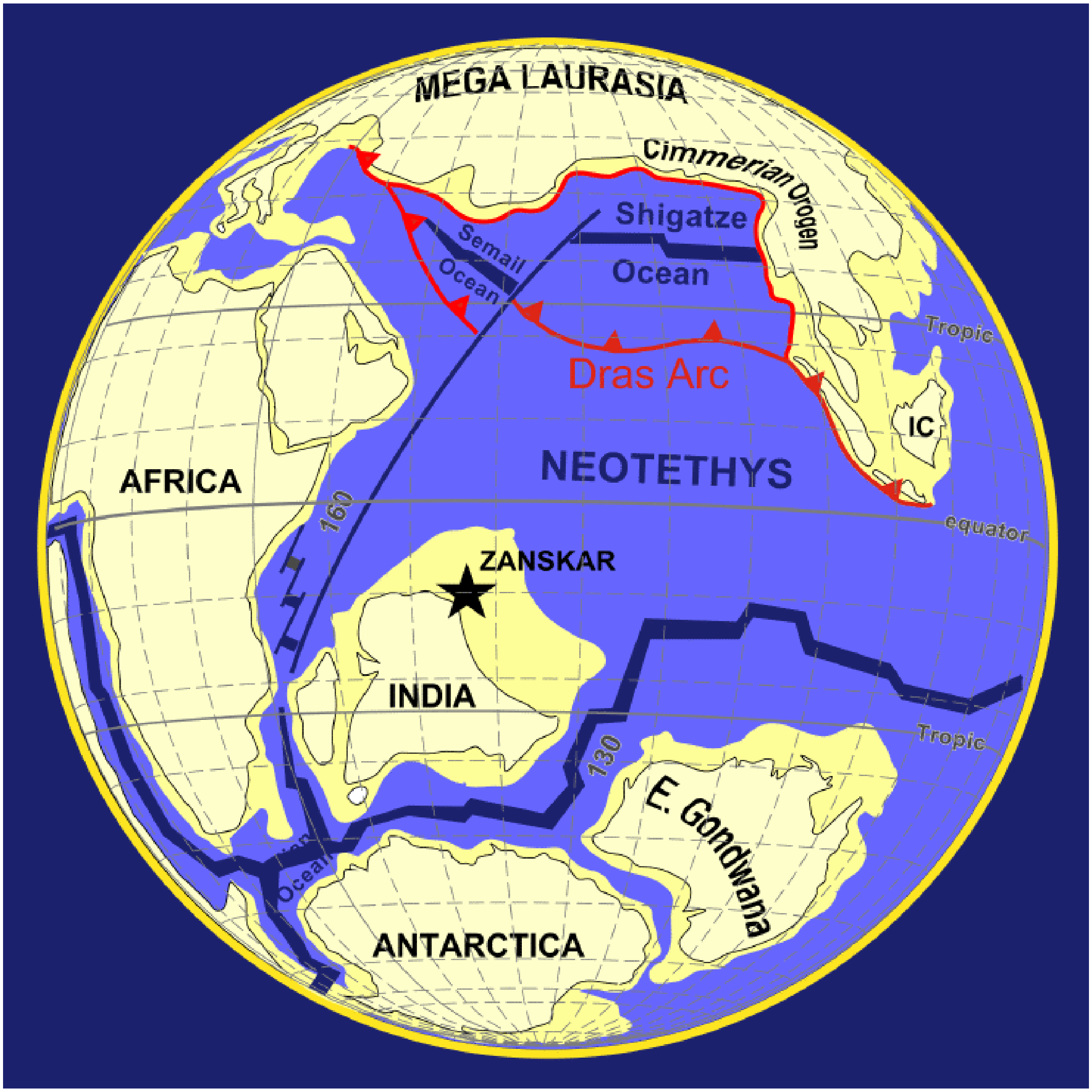


Figure A.3: **Plate tectonics- 100 Ma, Cretaceous period.**

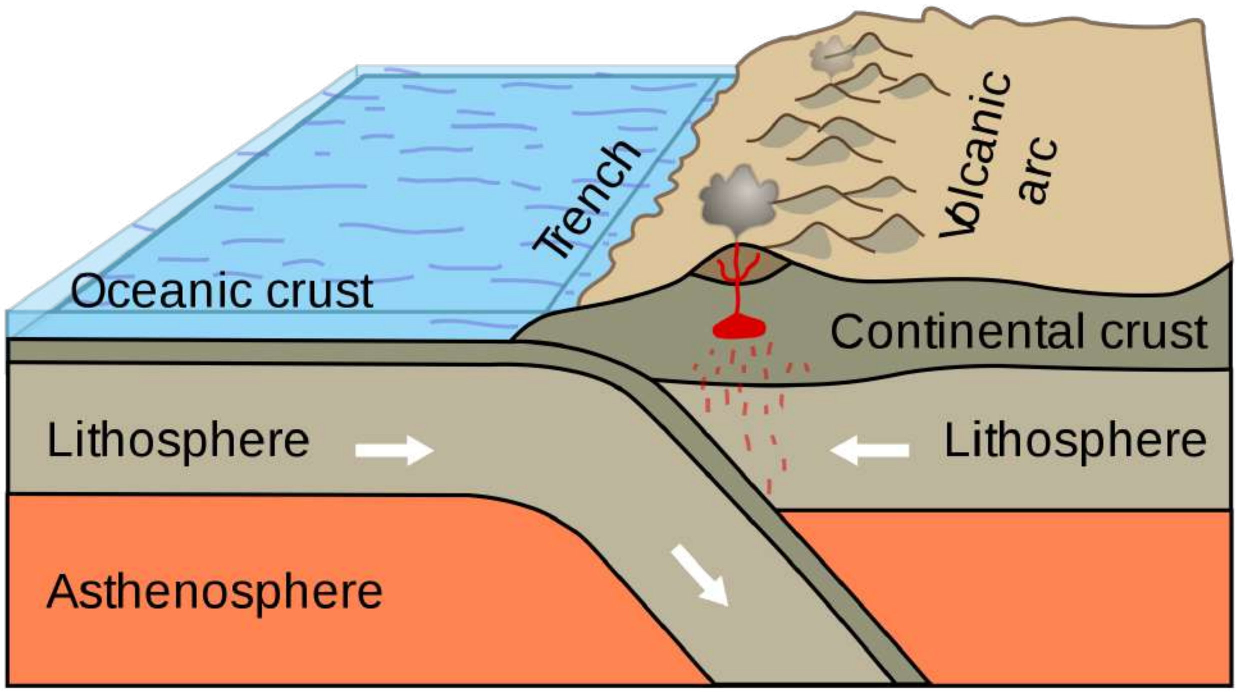


Figure A.4: **Oceanic-continental convergence resulting in subduction and volcanic arcs illustrates one effect of plate tectonics.**

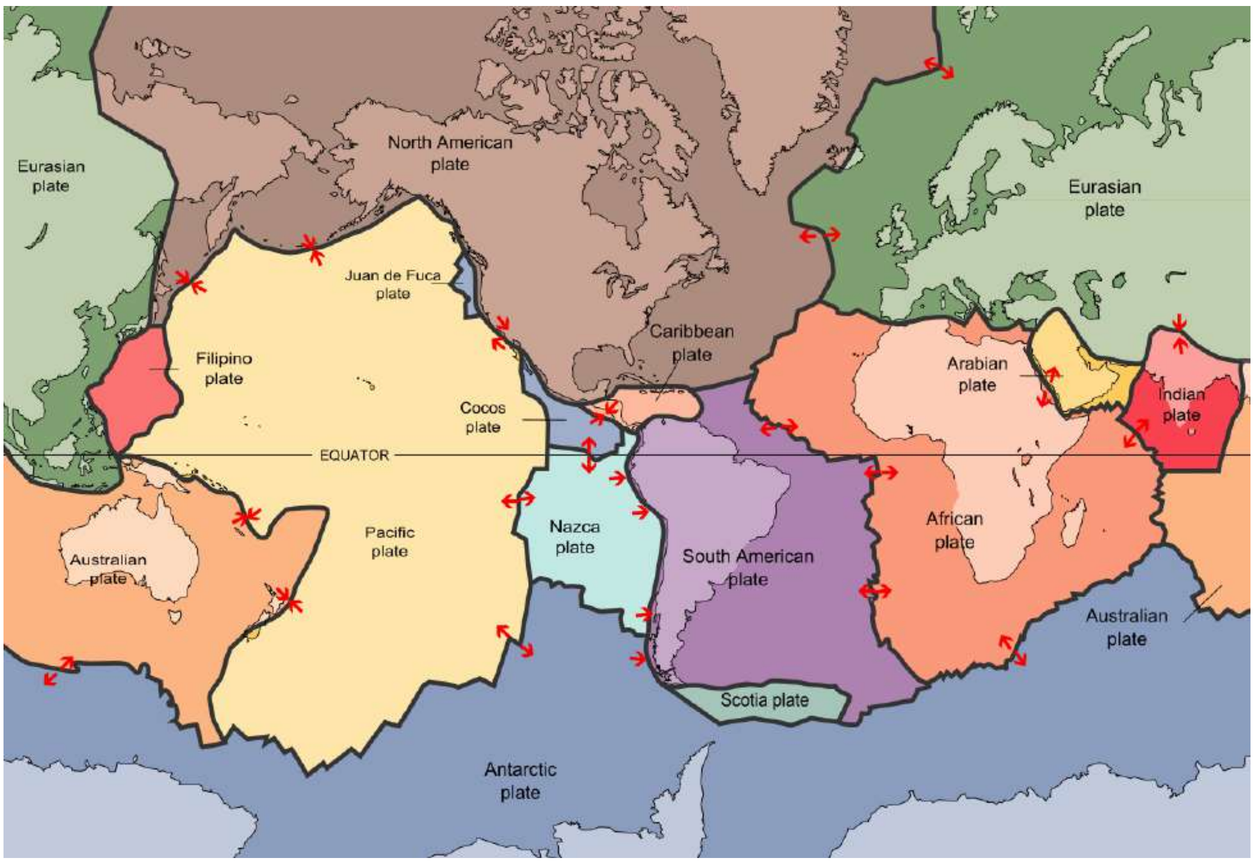


Figure A.5: **The major tectonic plates of the Earth. The key principle of plate tectonics is that the lithosphere exists as separate and distinct tectonic plates, which float on the fluid-like (visco-elastic solid) asthenosphere. The relative fluidity of the asthenosphere allows the tectonic plates to undergo motion in different directions.**

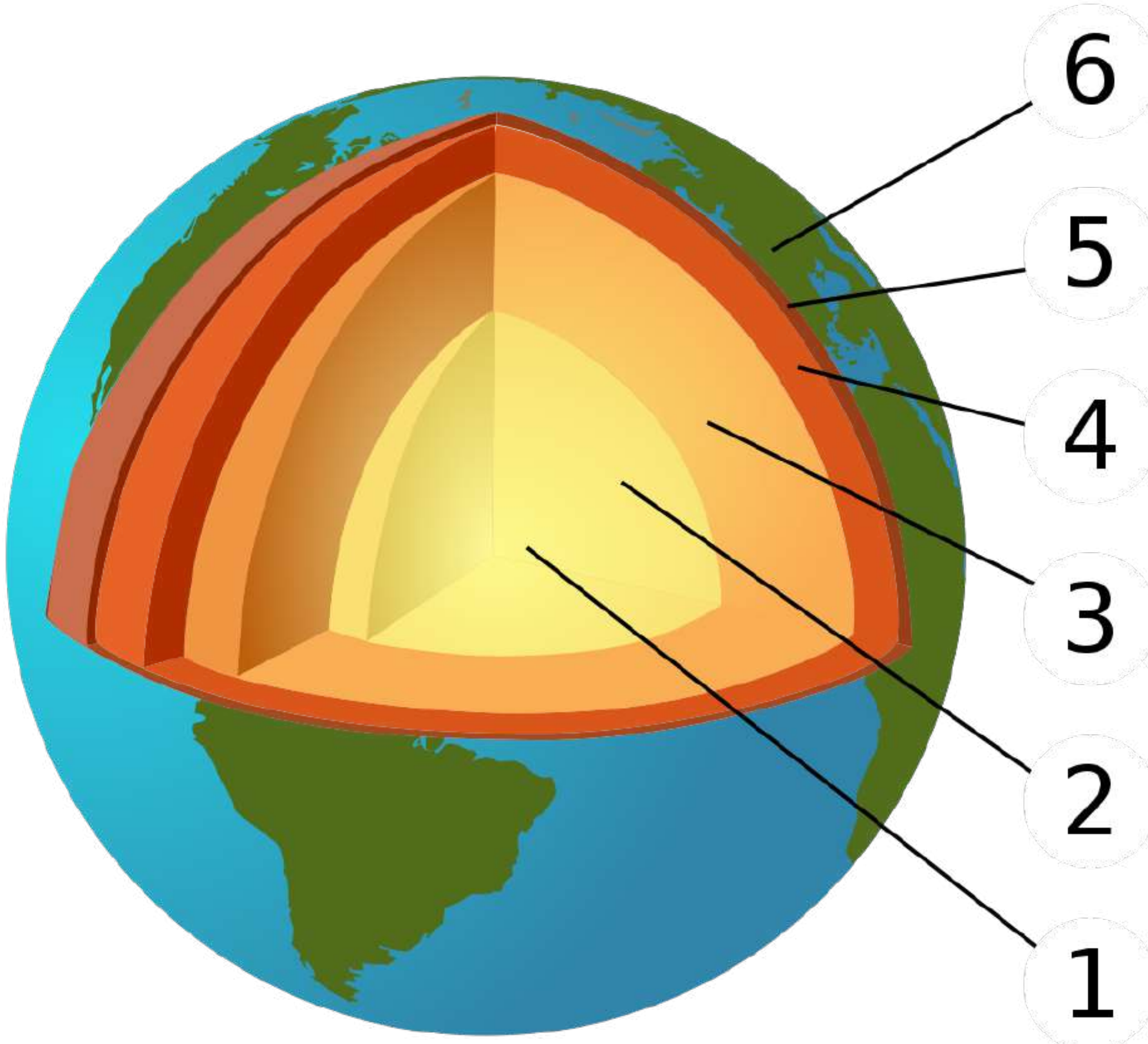


Figure A.6: **The Earth's layered structure. (1) inner core; (2) outer core; (3) lower mantle; (4) upper mantle; (5) lithosphere; (6) crust (part of the lithosphere). The extreme heat in the core of the earth is caused by the decay of radioactive elements. As the heat is conducted outward by convection currents, the currents are acted on by a combination of forces due to the earths rotation, and forces from the magnetic fields produced by the currents themselves. The resulting magnetic field of the earth as a function of geological time can be calculated, but it is a complex problem in magneto-hydrodynamics. Similar considerations hold for the sun's magnetic field and the sunspot cycle.**

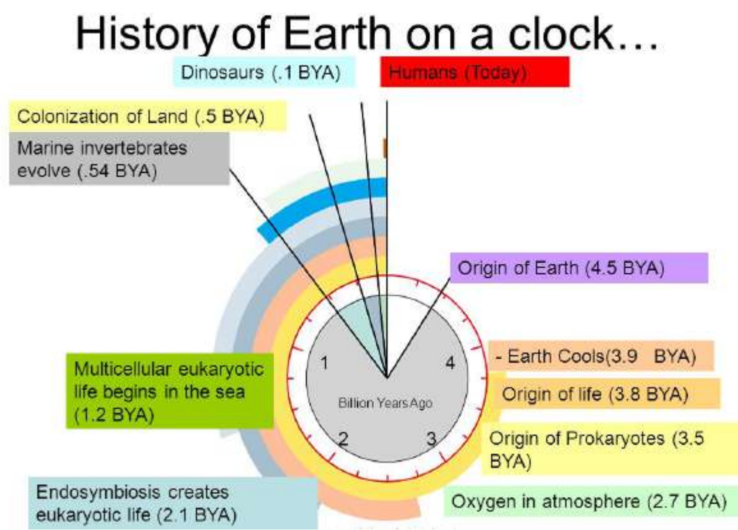


Figure A.7: **The Earth was formed 4.54 billion years ago. Life on earth originated approximately 3.8 billion years ago (3.8 BYA).**

Figure A.8: **This figure shows the relative sizes of the planets. Closest to the Sun are the relatively small terrestrial planets, Mercury, Venus, Earth and Mars, composed of metals and rock. Farther out are two gas giants, Jupiter and Saturn, which are composed mainly of hydrogen and helium. Still farther out are two ice giants, Uranus and Neptune, which are composed mainly of frozen water, frozen ammonia and frozen methane. The distances of the planets from the Sun shown in this figure are not realistic. The planetary orbits lie in roughly in the same plane, which is called the ecliptic, and all the planets circle the Sun in the same direction.**

Appendix B

THE HISTORY OF EVOLUTIONARY THEORIES

B.1 From Aristotle to Darwin

Before discussing modern theories of the origin and evolution of life on Earth, we will the ides of some early pioneers of this field.

Aristotle, (384 BC - 322 BC)

Aristotle was a very great organizer of knowledge, and his writings almost form a one-man encyclopedia. His best work was in biology, where he studied and classified more than five hundred animal species, many of which he also dissected. In Aristotle's classification of living things, he shows an awareness of the interrelatedness of species. This interrelatedness was much later used by Darwin as evidence for the theory of evolution. One cannot really say that Aristotle developed a theory of evolution, but he was groping towards the idea. In his history of animals, he writes:

"Nature proceeds little by little from lifeless things to animal life, so that it is impossible to determine either the exact line of demarcation, or on which side of the line an intermediate form should lie. Thus, next after lifeless things in the upward scale comes the plant. Of plants, one will differ from another as to its apparent amount of vitality. In a word, the whole plant kingdom, whilst devoid of life as compared with the animal, is yet endowed with life as compared with other corporeal entities. Indeed, there is observed in plants a continuous scale of ascent towards the animal."

Aristotle's classification of living things, starting at the bottom of the scale and going upward, is as follows: Inanimate matter, lower plants and sponges, higher plants, jellyfish, zoophytes and ascidians, molluscs, insects, jointed shellfish, octopuses and squids, fish and reptiles, whales, land mammals and man. The acuteness of Aristotle's observation and analysis can be seen from the fact that he classified whales and dolphins as mammals (where they belong) rather than as fish (where they superficially seem to belong, and where many ancient writers placed them).

Among Aristotle's biological writings, there appears a statement that clearly foreshadows the principle of natural selection, later independently discovered by Darwin and Wallace and fully developed by Darwin. Aristotle wrote: "Wheresoever, therefore... all parts of one whole happened like as if they were made for something, these were preserved, having been appropriately constituted by an internal spontaneity; and wheresoever things were not thus constituted, they perished, and still perish".

Averröes

During the Middle Ages, Aristotle's evolutionary ideas were revived and extended in the writings of the Islamic philosopher Averröes[1], who lived in Spain from 1126 to 1198. His writings had a great influence on western thought. Averroes shocked both his Moslem and his Christian readers by his thoughtful commentaries on the works of Aristotle, in which he maintained that the world was not created at a definite instant, but that it instead evolved over a long period of time, and is still evolving.

Like Aristotle, Averröes seems to have been groping towards the ideas of evolution which were later developed in geology by Lyell and in biology by Darwin and Wallace. Much of the scholastic philosophy written at the University of Paris during the 13th century was aimed at refuting the doctrines of Averroes; but nevertheless, his ideas survived and helped to shape the modern picture of the world.

The mystery of fossils

During the lifetime of Leonardo da Vinci (1452-1519) the existence of fossil shells in the rocks of high mountain ranges was recognized and discussed. "...the shells in Lombardy are at four levels", Leonardo wrote, "and thus it is everywhere, having been made at various times...The stratified stones of the mountains are all layers of clay, deposited one above the other by the various floods of the rivers." Leonardo had no patience with the explanation given by some of his contemporaries, that the shells had been carried to mountain tops by the deluge described in the Bible. "If the shells had been carried by the muddy waters of the deluge", he wrote, "they would have been mixed up, and separated from each other amidst the mud, and not in regular steps and layers." Nor did Leonardo agree with the opinion that the shells somehow grew within the rocks: "Such an opinion cannot exist in a brain of much reason", he wrote, "because here are the years of their growth, numbered on their shells, and there are large and small ones to be seen, which could not have grown without food, and could not have fed without motion...and here they could not move."

Leonardo believed that the fossil shells were once part of living organisms, that they were buried in strata under water, and much later lifted to the tops of mountains by geological upheavals. However his acute observations had little influence on the opinions of his contemporaries because they appear among the 4000 or so pages of notes which he wrote for himself but never published.

[1] Abul Walid Mahommed Ibn Achmed, Ibn Mahommed Ibn Rosched

It was left to the Danish scientist Niels Stensen (1638-1686) (usually known by his Latinized name, Steno) to independently rediscover and popularize the correct interpretation of fossils and of rock strata. Steno, who had studied medicine at the University of Leiden, was working in Florence, where his anatomical studies attracted the attention of the Grand Duke of Tuscany, Ferdinand II. When an enormous shark was caught by local fishermen, the Duke ordered that its head be brought to Steno for dissection. The Danish anatomist was struck by shape of the shark's teeth, which reminded him of certain curiously shaped stones called glossopetrae that were sometimes found embedded in larger rocks. Steno concluded that the similarity of form was not just a coincidence, and that the glossopetrae were in fact the teeth of once-living sharks which had become embedded in the muddy sediments at the bottom of the sea and gradually changed to stone. Steno used the corpuscular theory of matter, a forerunner of atomic theory, to explain how the composition of the fossils could have changed while their form remained constant. Steno also formulated a law of strata, which states that in the deposition of layers of sediment, later converted to rock, the oldest layers are at the bottom.

In England, the brilliant and versatile experimental scientist Robert Hooke (1635-1703) added to Steno's correct interpretation of fossils by noticing that some fossil species are not represented by any living counterparts. He concluded that "there have been many other Species of Creatures in former Ages, of which we can find none at present; and that 'tis not unlikely also but that there may be divers new kinds now, which have not been from the beginning."

Similar observations were made by the French naturalist, Georges-Louis Leclerc, Comte de Buffon (1707-1788), who wrote: "We have monuments taken from the bosom of the Earth, especially from the bottom of coal and slate mines, that demonstrate to us that some of the fish and plants that these materials contain do not belong to species currently existing." Buffon's position as keeper of the Jardin du Roi, the French botanical gardens, allowed him time for writing, and while holding this post he produced a 44-volume encyclopedia of natural history. In this enormous, clearly written, and popular work, Buffon challenged the theological doctrines which maintained that all species were created independently, simultaneously and miraculously, 6000 years ago. As evidence that species change, Buffon pointed to vestigial organs, such as the lateral toes of the pig, which may have had a use for the ancestors of the pig. He thought that the donkey might be a degenerate relative of the horse. Buffon believed the earth to be much older than the 6000 years allowed by the Bible, but his estimate, 75,000 years, greatly underestimated the true age of the earth.

The great Scottish geologist James Hutton (1726-1797) had a far more realistic picture of the true age of the earth. Hutton observed that some rocks seemed to have been produced by the compression of sediments laid down under water, while other rocks appeared to have hardened after previous melting. Thus he classified rocks as being either igneous or else sedimentary. He believed the features of the earth to have been produced by the slow action of wind, rain, earthquakes and other forces which can be observed today, and that these forces never acted with greater speed than they do now. This implied that the earth must be immensely old, and Hutton thought its age to be almost infinite. He believed that the forces which turned sea beds into mountain ranges drew their energy from the heat of the earth's molten core. Together with Steno, Hutton is considered to be one of the fathers of modern geology. His uniformitarian principles, and his belief in the great age of the earth were later given wide circulation by Charles Darwin's friend and mentor, Sir Charles Lyell (1797-1875), and they paved the way for Darwin's application of uniformitarianism to biology. At the time of his death, Hutton was working on a theory of biological evolution through natural selection, but his manuscripts on this subject remained unknown until 1946

Linnaeus, Lamarck and Erasmus Darwin

During the 17th and 18th centuries, naturalists had been gathering information on thousands of species of plants and animals. This huge, undigested heap of information was put into some order by the great Swedish naturalist, Carl von Linné (1707-1778), who is usually called by his Latin name, Carolus Linnaeus.

Linnaeus reclassified all living things, and he introduced a binomial nomenclature, so that each plant or animal became known by two names - the name of its genus, and the name of its species. In the classification of Linnaeus, the species within a given genus resemble each other very closely. Linnaeus also grouped related genera into classes, and related classes into orders. Later, the French anatomist, Cuvier (1769-1832), grouped related orders into phyla.

In France, the Chevalier J.B. de Lamarck (1744-1829), was struck by the close relationships between various animal species; and in 1809 he published a book entitled *Philosophie Zoologique*, in which he tried to explain this interrelatedness in terms of a theory of evolution. Lamarck explained the close similarity of the species within a genus by supposing these species to have evolved from a common ancestor. However, the mechanism of evolution which he postulated was seriously wrong, since he believed that acquired characteristics could be inherited.

Lamarck believed, for example, that giraffes stretched their necks slightly by reaching upward to eat the leaves of high trees. He believed that these slightly-stretched necks could be inherited; and in this way, Lamarck thought, the necks of giraffes have gradually become longer over many generations. Although his belief in the inheritability of acquired characteristics was a serious mistake, Lamarck deserves much credit for correctly maintaining that the close similarity between the species of a genus is due to their descent from a common ancestral species.

Meanwhile, in England, the brilliant physician-poet, Erasmus Darwin (1731-1802), who was considered by Coleridge to have "...a greater range of knowledge than any other man in Europe", had published *The Botanic Garden* and *Zoonomia* (1794). Darwin's first book, *The Botanic Garden*, was written in verse, and in the preface he stated that his purpose was "...to inlist imagination under the banner of science.." and to call the reader's attention to "the immortal works of the celebrated Swedish naturalist, Linnaeus". This book was immensely popular during Darwin's lifetime, but modern readers might find themselves wishing that he had used prose instead of poetry.

Darwin's second book, *Zoonomia*, is more interesting, since it contains a clear statement of the theory of evolution:

"...When we think over the great changes introduced into various animals", Darwin wrote, "as in horses, which we have exercised for different purposes of strength and swiftness, carrying burthens or in running races; or in dogs, which have been cultivated for strength and courage, as the bull-dog; or for acuteness of his sense of smell, as in the hound and spaniel; or for the swiftness of his feet, as the greyhound; or for his swimming in the water, or for drawing snow-sledges, as the rough-haired dogs of the north... and add to these the great change of shape and colour which we daily see produced in smaller animals from our domestication of them, as rabbits or pigeons;... when we revolve in our minds the great similarity of structure which obtains in all the warm-blooded animals, as well as quadrupeds, birds and amphibious animals, as in mankind, from the mouse and the bat to the elephant and whale; we are led to conclude that they have alike been produced from a similar living filament."

Erasmus Darwin's son, Robert, married Suzannah Wedgwood, the pretty and talented daughter of the famous potter, Josiah Wedgwood; and in 1809, (the same year in which Lamarck published his *Philosophie Zoologique*), she became the mother of Charles Darwin.

Charles Darwin

As a boy, Charles Darwin was fond of collecting and hunting, but he showed no special ability in school. His father, disappointed by his mediocre performance, once said to him: "You care for nothing but shooting, dogs and rat-catching; and you will be a disgrace to yourself, and to all your family."

Robert Darwin was determined that his son should not turn into an idle, sporting man, as he seemed to be doing, and when Charles was sixteen, he was sent to the University of Edinburgh to study medicine. However, Charles Darwin had such a sensitive and gentle disposition that he could not stand to see operations (performed, in those days, without chloroform). Besides, he had found out that his father planned to leave him enough money to live on comfortably; and consequently he didn't take his medical studies very seriously. However, some of his friends were scientists,and through them, Darwin became interested in geology and zoology.

Robert Darwin realized that his son did not want to become a physician, and, as an alternative, he sent Charles to Cambridge to prepare for the clergy. At Cambridge, Charles Darwin was very popular because of his cheerful, kind and honest character; but he was not a very serious student. Among his many friends, however, there were a few scientists, and they had a strong influence on him. The most important of Darwin's scientific friends were John Stevens Henslow, the Professor of Botany at Cambridge, and Adam Sedgwick, the Professor of Geology.

Remembering the things which influenced him at that time, Darwin wrote:

"During my last year at Cambridge, I read with care and profound interest Humboldt's *Personal Narrative of Travels to the Equinoctial Regions of America*. This work, and Sir J. Herschel's *Introduction to the Study of Natural Philosophy*, stirred up in me a burning desire

Figure B.1: **Erasmus Darwin (1731-1802), the grandfather of Charles Darwin, proposed a theory of evolution, but did not support it with enough experimental evidence to satisfy the naturalists of the time.**

to add even the most humble contribution to the noble structure of Natural Science. No one of a dozen books influenced me nearly so much as these. I copied out from Humboldt long passages about Teneriffe, and read them aloud to Henslow, Ramsay and Dawes... and some of the party declared that they would endeavour to go there; but I think they were only half in earnest. I was, however, quite in earnest, and got an introduction to a merchant in London to enquire about ships."

During the summer of 1831, Charles Darwin went to Wales to help Professor Sedgwick, who was studying the extremely ancient rock formations found there. When he returned to his father's house after this geological expedition, he found a letter from Henslow. This letter offered Darwin the post of unpaid naturalist on the *Beagle*, a small brig which was being sent by the British government to survey the coast of South America and to carry a chain of chronological measurements around the world.

Darwin was delighted and thrilled by this offer. He had a burning desire both to visit the glorious, almost-unknown regions described by his hero, Alexander von Humboldt, and to "add even the most humble contribution to the noble structure of Natural Science". His hopes and plans were blocked, however, by the opposition of his father, who felt that Charles was once again changing his vocation and drifting towards a life of sport and idleness. "If you can find any man of common sense who advises you to go", Robert Darwin told his son, "I will give my consent".

Deeply depressed by his father's words, Charles Darwin went to visit the estate of his uncle, Josiah Wedgwood, at Maer, where he always felt more comfortable than he did at home. In Darwin's words what happened next was the following:

"...My uncle sent for me, offering to drive me over to Shrewsbury and talk with my father, as my uncle thought that it would be wise in me to accept the offer. My father always maintained that my uncle was one of the most sensible men in the world, and he at once consented in the kindest possible manner. I had been rather extravagant while at

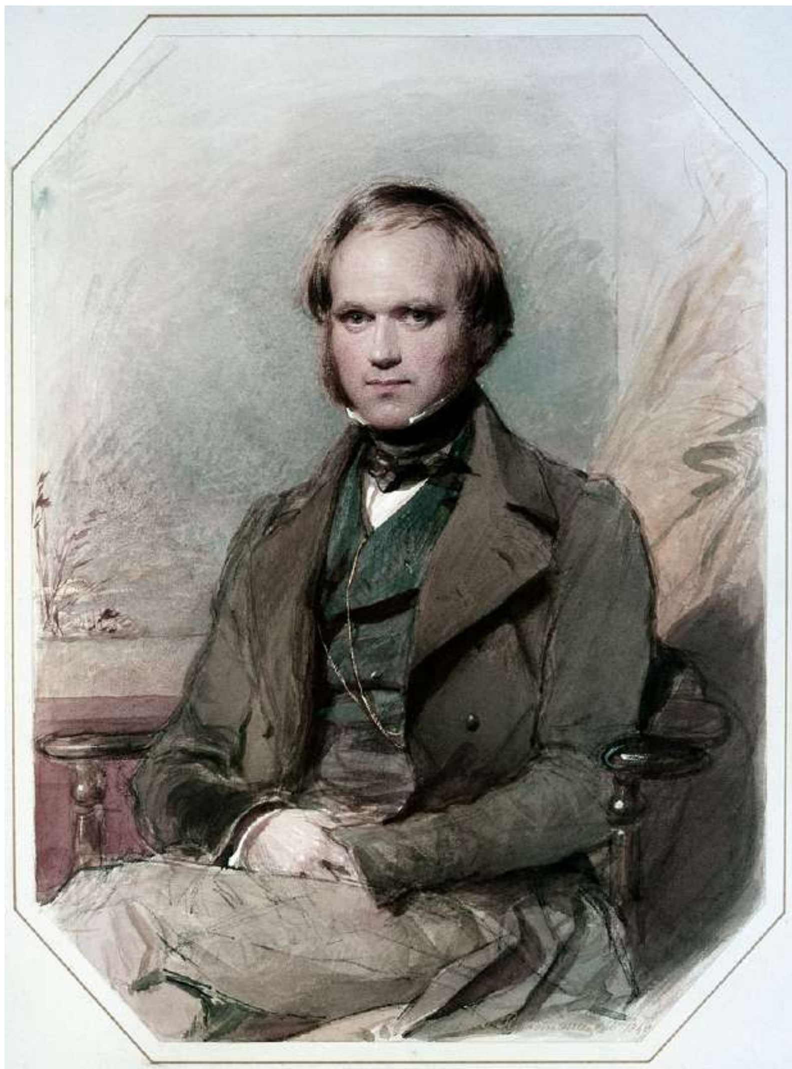


Figure B.2: **Charles Darwin as a young man. Public domain, Wikimedia Commons**

Cambridge, and to console my father, I said that 'I should be deuced clever to spend more than my allowance whilst on board the *Beagle*', but he answered with a smile, 'But they tell me you are very clever!'."

Thus, on December 27, 1831, Charles Darwin started on a five-year voyage around the world. Not only was this voyage destined to change Darwin's life, but also, more importantly, it was destined to change man's view of his place in nature.

Lyell's hypothesis

As the *Beagle* sailed out of Devonport in gloomy winter weather, Darwin lay in his hammock, 22 years old, miserably seasick and homesick, knowing that he would not see his family and friends for many years. To take his mind away from his troubles, Darwin read a new book, which Henslow had recommended: Sir Charles Lyell's *Principles of Geology*. "Read it by all means", Henslow had written, "for it is very interesting; but do not pay any attention to it except in regard to facts, for it is altogether wild as far as theory goes."

Reading Lyell's book with increasing excitement and absorption, Darwin could easily see what Henslow found objectionable: Lyell, a follower of the great Scottish geologist, James Hutton (1726-1797), introduced a revolutionary hypothesis into geology. According to Lyell, "No causes whatever have, from the earliest times to which we can look back, to the present, ever acted, but those now acting; and they have never acted with different degrees of energy from those which they now exert".

This idea seemed dangerous and heretical to deeply religious men like Henslow and Sedgwick. They believed that the earth's geology had been shaped by Noah's flood, and perhaps by other floods and catastrophes which had occurred before the time of Noah. The great geological features of the earth, its mountains, valleys and planes, they viewed as marks left behind by the various catastrophes through which the earth had passed.

All this was now denied by Lyell. He believed the earth to be enormously old - thousands of millions of years old. Over this vast period of time, Lyell believed, the long-continued action of slow forces had produced the geological features of the earth. Great valleys had been carved out by glaciers and by the slow action of rain and frost; and gradual changes in the level of the land, continued over enormous periods of time, had built up towering mountain ranges.

Lyell's belief in the immense age of the earth, based on geological evidence, made the evolutionary theories of Darwin's grandfather suddenly seem more plausible. Given such vast quantities of time, the long-continued action of small forces might produce great changes in biology as well as in geology!

By the time the *Beagle* had reached San Thiago in the Cape Verde Islands, Darwin had thoroughly digested Lyell's book, with its dizzying prospects. Looking at the geology of San Thiago, he realized "the wonderful superiority of Lyell's manner of treating geology". Features of the island which would have been incomprehensible on the basis of the usual Catastrophist theories were clearly understandable on the basis of Lyell's hypothesis.

As the *Beagle* slowly made its way southward along the South American coast, Darwin went on several expeditions to explore the interior. On one of these trips, he discovered

Figure B.3: **Plate showing Fuegans from the voyage of the Beagle. Wellcome Images, Wikimedia Commons**

some fossil bones in the red mud of a river bed. He carefully excavated the area around them, and found the remains of nine huge extinct quadrupeds. Some of them were as large as elephants, and yet in structure they seemed closely related to living South American species. For example, one of the extinct animals which Darwin discovered resembled an armadillo except for its gigantic size.

The *Beagle* rounded Cape Horn, lashed by freezing waves so huge that it almost floundered. After the storm, when the brig was anchored safely in the channel of Tierra del Fuego, Darwin noticed how a Fuegan woman stood for hours and watched the ship, while sleet fell and melted on her naked breast, and on the new-born baby she was nursing. He was struck by the remarkable degree to which the Fuegans had adapted to their frigid environment, so that they were able to survive with almost no shelter, and with no clothes except a few stiff animal skins, which hardly covered them, in weather which would have killed ordinary people.

In 1835, as the *Beagle* made its way slowly northward, Darwin had many chances to explore the Chilean coast - a spectacularly beautiful country, shadowed by towering ranges of the Andes. One day, near Concepcion Bay, he experienced the shocks of a severe earthquake.

"It came on suddenly, and lasted two minutes", Darwin wrote, "The town of Concepcion is now nothing more than piles and lines of bricks, tiles and timbers."

Measurements which Darwin made showed him that the shoreline near Concepcion had risen at least three feet during the quake; and thirty miles away, Fitzroy, the captain of the *Beagle*, discovered banks of mussels ten feet above the new high-water mark. This was dramatic confirmation of Lyell's theories! After having seen how much the level of the land was changed by a single earthquake, it was easy for Darwin to imagine that similar events, in the course of many millions of years, could have raised the huge wall of the Andes mountains.

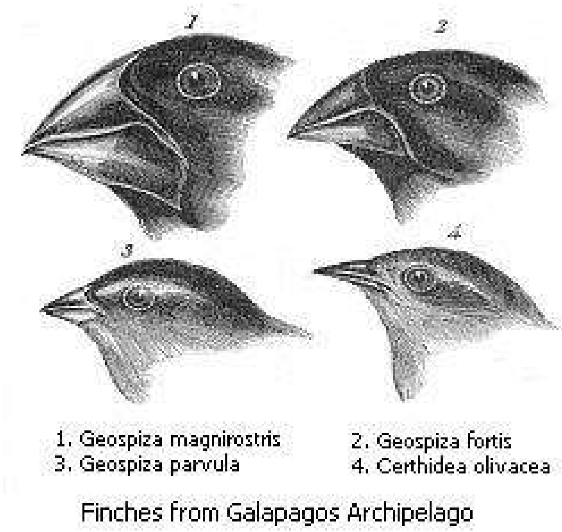


Figure B.4: **Darwin's finches. Public domain, Wikimedia Commons**

In September, 1835, the *Beagle* sailed westward to the Galapagos Islands, a group of small rocky volcanic islands off the coast of Peru. On these islands, Darwin found new species of plants and animals which did not exist anywhere else in the world. In fact, he discovered that each of the islands had its own species, similar to the species found on the other islands, but different enough to be classified separately.

The Galapagos Islands contained thirteen species of finches, found nowhere else in the world, all basically alike in appearance, but differing in certain features especially related to their habits and diet. As he turned these facts over in his mind, it seemed to Darwin that the only explanation was that the thirteen species of Galapagos finches were descended from a single species, a few members of which had been carried to the islands by strong winds blowing from the South American mainland.

"Seeing this gradation and diversity of structure in one small, intimately related group of birds", Darwin wrote, "one might really fancy that from an original paucity of birds in this archipelago, one species had been taken and modified for different ends... Facts such as these might well undermine the stability of species."

As Darwin closely examined the plants and animals of the Galapagos Islands, he could see that although they were not quite the same as the corresponding South American species, they were so strongly similar that it seemed most likely that all the Galapagos plants and animals had reached the islands from the South American mainland, and had since been modified to their present form.

The idea of the gradual modification of species could also explain the fact, observed by Darwin, that the fossil animals of South America were more closely related to African and Eurasian animals than were the living South American species. In other words, the fossil animals of South America formed a link between the living South American species and the corresponding animals of Europe, Asia and Africa. The most likely explanation for this was that the animals had crossed to America on a land bridge which had since been lost, and that they had afterwards been modified.

The Beagle continued its voyage westward, and Darwin had a chance to study the plants and animals of the Pacific Islands. He noticed that there were no mammals on these islands, except bats and a few mammals brought by sailors. It seemed likely to Darwin that all the species of the Pacific Islands had reached them by crossing large stretches of water after the volcanic islands had risen from the ocean floor; and this accounted for the fact that so many classes were missing. The fact that each group of islands had its own particular species, found nowhere else in the world, seemed to Darwin to be strong evidence that the species had been modified after their arrival. The strange marsupials of the isolated Australian continent also made a deep impression on Darwin.

The Origin of Species

Darwin had left England on the Beagle in 1831, an immature young man of 22, with no real idea of what he wanted to do with his life. He returned from the five-year voyage in 1836, a mature man, confirmed in his dedication to science, and with formidable powers of observation, deduction and generalization. Writing of the voyage, Darwin says:

"I have always felt that I owe to the voyage the first real education of my mind... Everything about which I thought or read was made to bear directly on what I had seen, or was likely to see, and this habit was continued during the five years of the voyage. I feel sure that it was this training which has enabled me to do whatever I have done in science."

Darwin returned to England convinced by what he had seen on the voyage that plant and animal species had not been independently and miraculously created, but that they had been gradually modified to their present form over millions of years of geological time.

Darwin was delighted to be home and to see his family and friends once again. To his uncle, Josiah Wedgwood, he wrote:

"My head is quite confused from so much delight, but I cannot allow my sister to tell you first how happy I am to see all my dear friends again... I am most anxious once again to see Maer and all its inhabitants."

In a letter to Henslow, he said:

"My dear Henslow, I do long to see you. You have been the kindest friend to me that ever man possessed. I can write no more, for I am giddy with joy and confusion."

In 1837, Darwin took lodgings at Great Marlborough Street in London, where he could work on his geological and fossil collections. He was helped in his work by Sir Charles Lyell, who became Darwin's close friend. In 1837 Darwin also began a notebook on *Transmutation of Species*. His *Journal of researches into the geology and natural history of the various countries visited by the H.M.S. Beagle* was published in 1839, and it quickly became a best-seller. It is one of the most interesting travel books ever written, and since its publication it has been reissued more than a hundred times.

These were very productive years for Darwin, but he was homesick, both for his father's home at the Mount and for his uncle's nearby estate at Maer, with its galaxy of attractive daughters. Remembering his many happy visits to Maer, he wrote:

"In the summer, the whole family used often to sit on the steps of the old portico, with the flower-garden in front, and with the steep, wooded bank opposite the house reflected in the lake, with here and there a fish rising, or a water-bird paddling about. Nothing has left a more vivid picture in my mind than these evenings at Maer."

In the summer of 1838, tired of his bachelor life in London, Darwin wrote in his diary:

"My God, it is intolerable to think of spending one's whole life like a neuter bee, working, working, and nothing after all! Imagine living all one's days in smoky, dirty London! Only picture to yourself a nice soft wife on a sofa with a good fire, and books and music perhaps.. Marry! Marry! Marry! Q.E.D."

Having made this decision, Darwin went straight to Maer and proposed to his pretty cousin, Emma Wedgwood, who accepted him at once, to the joy of both families. Charles and Emma Darwin bought a large and pleasant country house at Down, fifteen miles south of London; and there, in December, 1839, the first of their ten children was born.

Darwin chose this somewhat isolated place for his home because he was beginning to show signs of a chronic illness, from which he suffered for the rest of his life. His strength was very limited, and he saved it for his work by avoiding social obligations. His illness was never accurately diagnosed during his own lifetime, but the best guess of modern doctors is that he had Chagas' disease, a trypanasome infection transmitted by the bite of a South American blood-sucking bug.

Darwin was already convinced that species had changed over long periods of time, but what were the forces which caused this change? In 1838 he found the answer:

"I happened to read for amusement Malthus on *Population*", he wrote, "and being well prepared to appreciate the struggle for existence which everywhere goes on from long-continued observation of the habits of animals and plants, it at once struck me that under these circumstances favorable variations would tend to be preserved, and unfavorable ones destroyed. The result would be the formation of new species"

"Here, then, I had at last got a theory by which to work; but I was so anxious to avoid prejudice that I determined not for some time to write down even the briefest sketch of it. In June, 1842, I first allowed myself the satisfaction of writing a very brief abstract of my theory in pencil in 33 pages; and this was enlarged during the summer of 1844 into one of 230 pages".

All of Darwin's revolutionary ideas were contained in the 1844 abstract, but he did not publish it! Instead, in an incredible Copernicus-like procrastination, he began a massive treatise on barnacles, which took him eight years to finish! Probably Darwin had a premonition of the furious storm of hatred and bigotry which would be caused by the publication of his heretical ideas.

Finally, in 1854, he wrote to his friend, Sir Joseph Hooker (the director of Kew Botanical Gardens), to say that he was at last resuming his work on the origin of species. Both Hooker and Lyell knew of Darwin's work on evolution, and for many years they had been urging him to publish it. By 1835, he had written eleven chapters of a book on the origin of species through natural selection; but he had begun writing on such a vast scale that the book might have run to four or five heavy volumes, which could have taken Darwin the rest of his life to complete.

Fortunately, this was prevented by the arrival at Down House of a bombshell in the form of a letter from a young naturalist named Alfred Russell Wallace. Like Darwin, Wallace had read Malthus' book *On Population*, and in a flash of insight during a period of fever in Malaya, he had arrived at a theory of evolution through natural selection which was precisely the same as the theory on which Darwin had been working for twenty years! Wallace enclosed with his letter a short paper entitled *On the Tendency of Varieties to Depart Indefinitely From the Original Type*. It was a perfect summary of Darwin's theory of evolution!

"I never saw a more striking coincidence", the stunned Darwin wrote to Lyell, "If Wallace had my MS. sketch, written in 1842, he could not have made a better short abstract! Even his terms now stand as heads of my chapters... I should be extremely glad now to publish a sketch of my general views in about a dozen pages or so; but I cannot persuade myself that I can do so honourably... I would far rather burn my whole book than that he or any other man should think that I have behaved in a paltry spirit."

Both Lyell and Hooker acted quickly and firmly to prevent Darwin from suppressing his own work, as he was inclined to do. In the end, they found a happy solution: Wallace's paper was read to the Linnean Society together with a short abstract of Darwin's work, and the two papers were published together in the proceedings of the society. The members of the Society listened in stunned silence. As Hooker wrote to Darwin the next day, the subject was "too novel and too ominous for the old school to enter the lists before armouring."

Lyell and Hooker then persuaded Darwin to write a book of moderate size on evolution through natural selection. As a result, in 1859, he published *The Origin of Species*, which ranks, together with Newton's *Principia* as one of the two greatest scientific books of all time. What Newton did for physics, Darwin did for biology: He discovered the basic theoretical principle which brings together all the experimentally-observed facts and makes them comprehensible; and he showed in detail how this basic principle can account for the facts in a very large number of applications.

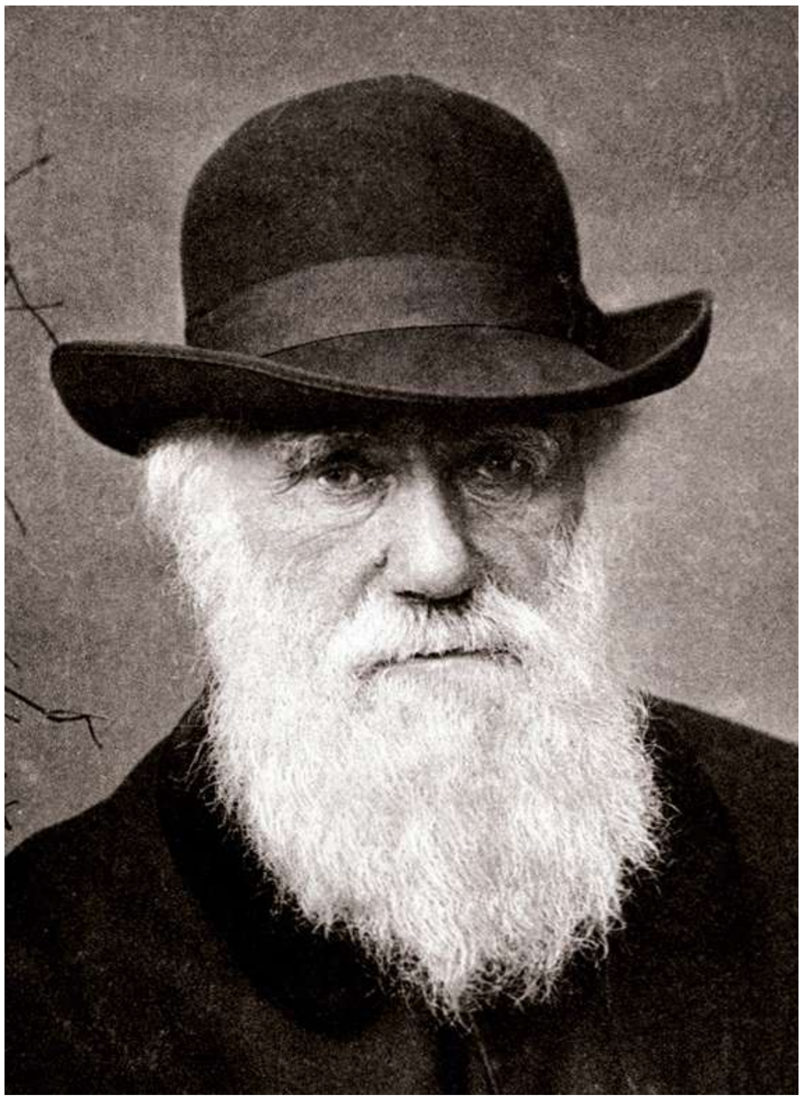


Figure B.5: **Charles Darwin in 1880. The photograph is by Elliott and Fry. Public domain, Wikimedia Commons**

Figure B.6: **"Man is is But a Worm", a cartoon, published in Punch in 1882. Public domain, Wikimedia Commons**

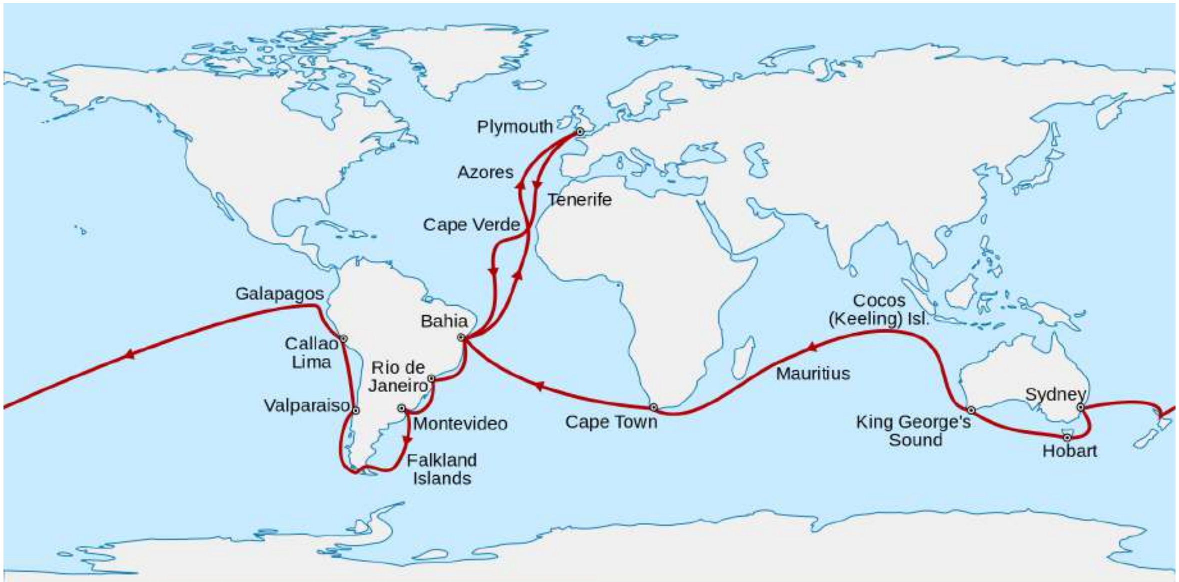


Figure B.7: **A map showing the *Beagle's* circumnavigation of the world.**

Figure B.8: **As *HMS Beagle* surveyed the coasts of South America, Darwin theorised about geology and the extinction of giant mammals.**

Appendix C

MODERN THEORIES OF THE ORIGIN OF LIFE

C.1 Molecular biology and the origin of life

Molecular biology

Charles Darwin postulated that natural selection acts on small inheritable variations in the individual members of a species. His opponents objected that these slight variations would be averaged away by interbreeding. Darwin groped after an answer to this objection, but he did not have one. However, unknown to Darwin, the answer had been uncovered several years earlier by an obscure Augustinian monk, Gregor Mendel, who was born in Silesia in 1822, and who died in Bohemia in 1884.

Mendel loved both botany and mathematics, and he combined these two interests in his hobby of breeding peas in the monastery garden. Mendel carefully self-pollinated his pea plants, and then wrapped the flowers to prevent pollination by insects. He kept records of the characteristics of the plants and their offspring, and he found that dwarf peas always breed true - they invariably produce other dwarf plants. The tall variety of pea plants, pollinated with themselves, did not always breed true, but Mendel succeeded in isolating a strain of true-breeding tall plants which he inbred over many generations.

Next he crossed his true-breeding tall plants with the dwarf variety and produced a generation of hybrids. All of the hybrids produced in this way were tall. Finally Mendel self-pollinated the hybrids and recorded the characteristics of the next generation. Roughly one quarter of the plants in this new generation were true-breeding tall plants, one quarter were true-breeding dwarfs, and one half were tall but not true-breeding.

Gregor Mendel had in fact discovered the existence of dominant and recessive genes. In peas, dwarfism is a recessive characteristic, while tallness is dominant. Each plant has two sets of genes, one from each parent. Whenever the gene for tallness is present, the plant is tall, regardless of whether it also has a gene for dwarfism. When Mendel crossed the pure-breeding dwarf plants with pure-breeding tall ones, the hybrids received one type of gene from each parent. Each hybrid had a tall gene and a dwarf gene; but the tall gene was dominant, and therefore all the hybrids were tall. When the hybrids were self-pollinated or crossed with each other, a genetic lottery took place. In the next generation, through the laws of chance, a quarter of the plants had two dwarf genes, a quarter had two tall genes, and half had one of each kind.

Mendel published his results in the *Transactions of the Brünn Natural History Society* in 1865, and no one noticed his paper[1]. At that time, Austria was being overrun by the Prussians, and people had other things to think about. Mendel was elected Abbot of his monastery; he grew too old and fat to bend over and cultivate his pea plants; his work on heredity was completely forgotten, and he died never knowing that he would one day be considered to be the founder of modern genetics.

In 1900 the Dutch botanist named Hugo de Vries, working on evening primroses, independently rediscovered Mendel's laws. Before publishing, he looked through the literature to see whether anyone else had worked on the subject, and to his amazement he found that Mendel had anticipated his great discovery by 35 years. De Vries could easily have published his own work without mentioning Mendel, but his honesty was such that he gave Mendel full credit and mentioned his own work only as a confirmation of Mendel's laws. Astonishingly, the same story was twice repeated elsewhere in Europe during the same year. In 1900, two other botanists (Correns in Berlin and Tschermak in Vienna) independently rediscovered Mendel's laws, looked through the literature, found Mendel's 1865 paper, and gave him full credit for the discovery.

Besides rediscovering the Mendelian laws for the inheritance of dominant and recessive characteristics, de Vries made another very important discovery: He discovered genetic mutations - sudden unexplained changes of form which can be inherited by subsequent generations. In growing evening primroses, de Vries found that sometimes, but very rarely, a completely new variety would suddenly appear, and he found that the variation could be propagated to the following generations. Actually, mutations had been observed before the time of de Vries. For example, a short-legged mutant sheep had suddenly appeared during the 18th century; and stock-breeders had taken advantage of this mutation to breed sheep that could not jump over walls. However, de Vries was the first scientist to study and describe mutations. He noticed that most mutations are harmful, but that a very few are beneficial, and those few tend in nature to be propagated to future generations.

After the rediscovery of Mendel's work by de Vries, many scientists began to suspect that chromosomes might be the carriers of genetic information. The word "chromosome" had been invented by the German physiologist, Walther Flemming, to describe the long, threadlike bodies which could be seen when cells were stained and examined through, the microscope during the process of division. It had been found that when an ordinary cell divides, the chromosomes also divide, so that each daughter cell has a full set of chromosomes.

The Belgian cytologist, Edouard van Benedin, had shown that in the formation of sperm and egg cells, the sperm and egg receive only half of the full number of chromosomes. It

[1] Mendel sent a copy of his paper to Darwin; but Darwin, whose German was weak, seems not to have read it.

had been found that when the sperm of the father combines with the egg of the mother in sexual reproduction, the fertilized egg again has a full set of chromosomes, half coming from the mother and half from the father. This was so consistent with the genetic lottery studied by Mendel, de Vries and others, that it seemed almost certain that chromosomes were the carriers of genetic information.

The number of chromosomes was observed to be small (for example, each normal cell of a human has 46 chromosomes); and this made it obvious that each chromosome must contain thousands of genes. It seemed likely that all of the genes on a particular chromosome would stay together as they passed through the genetic lottery; and therefore certain characteristics should always be inherited together.

This problem had been taken up by Thomas Hunt Morgan, a professor of experimental zoology working at Colombia University. He found it convenient to work with fruit flies, since they breed with lightning-like speed and since they have only four pairs of chromosomes.

Morgan found that he could raise enormous numbers of these tiny insects with almost no effort by keeping them in gauze-covered glass milk bottles, in the bottom of which he placed mashed bananas. In 1910, Morgan found a mutant white-eyed male fly in one of his milk-bottle incubators. He bred this fly with a normal red-eyed female, and produced hundreds of red-eyed hybrids. When he crossed the red-eyed hybrids with each other, half of the next generation were red-eyed females, a quarter were red-eyed males, and a quarter were white-eyed males. There was not one single white-eyed female! This indicated that the mutant gene for white eyes was on the same chromosome as the gene for the male sex.

As Morgan continued his studies of genetic linkages, however, it became clear that the linkages were not absolute. There was a tendency for all the genes on the same chromosome to be inherited together; but on rare occasions there were "crosses", where apparently a pair of chromosomes broke at some point and exchanged segments. By studying these crosses statistically, Morgan and his "fly squad" were able to find the relative positions of genes on the chromosomes. They reasoned that the probability for a cross to separate two genes should be proportional to the distance between the two genes on the chromosome. In this way, after 17 years of work and millions of fruit flies, Thomas Hunt Morgan and his coworkers were able to make maps of the fruit fly chromosomes showing the positions of the genes.

This work had been taken a step further by Hermann J. Muller, a member of Morgan's "fly squad", who exposed hundreds of fruit flies to X-rays. The result was a spectacular outbreak of man-made mutations in the next generation.

"They were a motley throng", recalled Muller. Some of the mutant flies had almost no wings, others bulging eyes, and still others brown, yellow or purple eyes; some had no bristles, and others curly bristles. Muller's experiments indicated that mutations can be produced by radiation-induced physical damage; and he guessed that such damage alters the chemical structure of genes.

In spite of the brilliant work by Morgan and his collaborators, no one had any idea of what a gene really was.

The structure of DNA

Until 1944, most scientists had guessed that the genetic message was carried by the proteins of the chromosome. In 1944, however, O.T. Avery and his co-workers at the laboratory of the Rockefeller Institute in New York performed a critical experiment, which proved that the material which carries genetic information is not protein, but deoxyribonucleic acid (DNA) - a giant chainlike molecule which had been isolated from cell nuclei by the Swiss chemist, Friedrich Miescher.

Avery had been studying two different strains of pneumococci, the bacteria which cause pneumonia. One of these strains, the S-type, had a smooth coat, while the other strain, the R-type, lacked an enzyme needed for the manufacture of a smooth carbohydrate coat. Hence, R-type pneumococci had a rough appearance under the microscope. Avery and his co-workers were able to show that an extract from heat-killed S-type pneumococci could convert the living R-type species permanently into S-type; and they also showed that this extract consisted of pure DNA.

In 1947, the Austrian-American biochemist, Erwin Chargaff, began to study the long, chainlike DNA molecules. It had already been shown by Levine and Todd that chains of DNA are built up of four bases: adenine (A), thymine (T), guanine (G) and cytosine (C), held together by a sugar-phosphate backbone. Chargaff discovered that in DNA from the nuclei of living cells, the amount of A always equals the amount of T; and the amount of G always equals the amount of C.

When Chargaff made this discovery, neither he nor anyone else understood its meaning. However, in 1953, the mystery was completely solved by Rosalind Franklin and Maurice Wilkins at Kings College, London, together with James Watson and Francis Crick at Cambridge University. By means of X-ray diffraction techniques, Wilkins and Franklin obtained crystallographic information about the structure of DNA. Using this information, together with Linus Pauling's model-building methods, Crick and Watson proposed a detailed structure for the giant DNA molecule.

The discovery of the molecular structure of DNA was an event of enormous importance for genetics, and for biology in general. The structure was a revelation! The giant, helical DNA molecule was like a twisted ladder: Two long, twisted sugar-phosphate backbones formed the outside of the ladder, while the rungs were formed by the base pairs, A, T, G and C. The base adenine (A) could only be paired with thymine (T), while guanine (G) fit only with cytosine (C). Each base pair was weakly joined in the center by hydrogen bonds - in other words, there was a weak point in the center of each rung of the ladder - but the bases were strongly attached to the sugar-phosphate backbone. In their 1953 paper, Crick and Watson wrote:

"It has not escaped our notice that the specific pairing we have postulated suggests a possible copying mechanism for genetic material". Indeed, a sudden blaze of understanding illuminated the inner workings of heredity, and of life itself.

If the weak hydrogen bonds in the center of each rung were broken, the ladderlike DNA macromolecule could split down the center and divide into two single strands. Each single strand would then become a template for the formation of a new double-stranded molecule.

Because of the specific pairing of the bases in the Watson-Crick model of DNA, the two strands had to be complementary. T had to be paired with A, and G with C. Therefore, if the sequence of bases on one strand was (for example) TTTGCTAAAGGTGAACCA... , then the other strand necessarily had to have the sequence AAACGATTTCCACTTGGT... The Watson-Crick model of DNA made it seem certain that all the genetic information needed for producing a new individual is coded into the long, thin, double-stranded DNA molecule of the cell nucleus, written in a four-letter language whose letters are the bases, adenine, thymine, guanine and cytosine.

The solution of the DNA structure in 1953 initiated a new kind of biology - molecular biology. This new discipline made use of recently-discovered physical techniques - X-ray diffraction, electron microscopy, electrophoresis, chromatography, ultracentrifugation, radioactive tracer techniques, autoradiography, electron spin resonance, nuclear magnetic resonance and ultraviolet spectroscopy. In the 1960's and 1970's, molecular biology became the most exciting and rapidly-growing branch of science.

Protein structure

In England, J.D. Bernal and Dorothy Crowfoot Hodgkin pioneered the application of X-ray diffraction methods to the study of complex biological molecules. In 1949, Hodgkin determined the structure of penicillin; and in 1955, she followed this with the structure of vitamin B12. In 1960, Max Perutz and John C. Kendrew obtained the structures of the blood proteins myoglobin and hemoglobin. This was an impressive achievement for the Cambridge crystallographers, since the hemoglobin molecule contains roughly 12,000 atoms.

The structure obtained by Perutz and Kendrew showed that hemoglobin is a long chain of amino acids, folded into a globular shape, like a small, crumpled ball of yarn. They found that the amino acids with an affinity for water were on the outside of the globular molecule; while the amino acids for which contact with water was energetically unfavorable were hidden on the inside. Perutz and Kendrew deduced that the conformation of the protein - the way in which the chain of amino acids folded into a 3-dimensional structure - was determined by the sequence of amino acids in the chain.

In 1966, D.C. Phillips and his co-workers at the Royal Institution in London found the crystallographic structure of the enzyme lysozyme (an egg-white protein which breaks down the cell walls of certain bacteria). Again, the structure showed a long chain of amino acids, folded into a roughly globular shape. The amino acids with hydrophilic groups were on the outside, in contact with water, while those with hydrophobic groups were on the inside. The structure of lysozyme exhibited clearly an active site, where sugar molecules of bacterial cell walls were drawn into a mouth-like opening and stressed by electrostatic forces, so that bonds between the sugars could easily be broken.

Meanwhile, at Cambridge University, Frederick Sanger developed methods for finding the exact sequence of amino acids in a protein chain. In 1945, he discovered a compound (2,4-dinitrofluorobenzene) which attaches itself preferentially to one end of a chain of amino acids. Sanger then broke down the chain into individual amino acids, and determined which of them was connected to his reagent. By applying this procedure many times to fragments of larger chains, Sanger was able to deduce the sequence of amino acids in complex proteins. In 1953, he published the sequence of insulin. This led, in 1964, to the synthesis of insulin.

The biological role and structure of proteins which began to emerge was as follows: A mammalian cell produces roughly 10,000 different proteins. All enzymes are proteins; and the majority of proteins are enzymes - that is, they catalyze reactions involving other biological molecules. All proteins are built from chainlike polymers, whose monomeric sub-units are the following twenty amino acids: glycine, aniline, valine, isoleucine, leucine, serine, threonine, proline, aspartic acid, glutamic acid, lysine, arginine, asparagine, glutamine, cysteine, methionine, tryptophan, phenylalanine, tyrosine and histidine. These individual amino acid monomers may be connected together into a polymer (called a polypeptide) in any order - hence the great number of possibilities. In such a polypeptide, the backbone is a chain of carbon and nitrogen atoms showing the pattern ...-C-C-N-C-C-N-C-C-N-...and so on. The -C-C-N- repeating unit is common to all amino acids. Their individuality is derived from differences in the side groups which are attached to the universal -C-C-N- group.

Some proteins, like hemoglobin, contain metal atoms, which may be oxidized or reduced as the protein performs its biological function. Other proteins, like lysozyme, contain no metal atoms, but instead owe their biological activity to an active site on the surface of the protein molecule. In 1909, the English physician, Archibald Garrod, had proposed a one-gene-one-protein hypothesis. He believed that hereditary diseases are due to the absence of specific enzymes. According to Garrod's hypothesis, damage suffered by a gene results in the faulty synthesis of the corresponding enzyme, and loss of the enzyme ultimately results in the symptoms of the hereditary disease.

In the 1940's, Garrod's hypothesis was confirmed by experiments on the mold, Neurospora, performed at Stanford University by George Beadle and Edward Tatum. They demonstrated that mutant strains of the mold would grow normally, provided that specific extra nutrients were added to their diets. The need for these dietary supplements could in every case be traced to the lack of a specific enzyme in the mutant strains. Linus Pauling later extended these ideas to human genetics by showing that the hereditary disease, sickle-cell anemia, is due to a defect in the biosynthesis of hemoglobin.

RNA and ribosomes

Since DNA was known to carry the genetic message, coded into the sequence of the four nucleotide bases, A, T, G and C, and since proteins were known to be composed of specific sequences of the twenty amino acids, it was logical to suppose that the amino acid sequence in a protein was determined by the base sequence of DNA. The information somehow had to be read from the DNA and used in the biosynthesis of the protein.

It was known that, in addition to DNA, cells also contain a similar, but not quite identical, polynucleotide called ribonucleic acid (RNA). The sugar-phosphate backbone of RNA was known to differ slightly from that of DNA; and in RNA, the nucleotide thymine

(T) was replaced by a chemically similar nucleotide, uracil (U). Furthermore, while DNA was found only in cell nuclei, RNA was found both in cell nuclei and in the cytoplasm of cells, where protein synthesis takes place. Evidence accumulated indicating that genetic information is first transcribed from DNA to RNA, and afterwards translated from RNA into the amino acid sequence of proteins.

At first, it was thought that RNA might act as a direct template, to which successive amino acids were attached. However, the appropriate chemical complementarity could not be found; and therefore, in 1955, Francis Crick proposed that amino acids are first bound to an adaptor molecule, which is afterward bound to RNA.

In 1956, George Emil Palade of the Rockefeller Institute used electron microscopy to study subcellular particles rich in RNA (ribosomes). Ribosomes were found to consist of two subunits - a smaller subunit, with a molecular weight one million times the weight of a hydrogen atom, and a larger subunit with twice this weight.

It was shown by means of radioactive tracers that a newly synthesized protein molecule is attached temporarily to a ribosome, but neither of the two subunits of the ribosome seemed to act as a template for protein synthesis. Instead, Palade and his coworkers found that genetic information is carried from DNA to the ribosome by a messenger RNA molecule (mRNA). Electron microscopy revealed that mRNA passes through the ribosome like a punched computer tape passing through a tape-reader. It was found that the adapter molecules, whose existence Crick had postulated, were smaller molecules of RNA; and these were given the name "transfer RNA" (tRNA). It was shown that, as an mRNA molecule passes through a ribosome, amino acids attached to complementary tRNA adaptor molecules are added to the growing protein chain.

The relationship between DNA, RNA, the proteins and the smaller molecules of a cell was thus seen to be hierarchical: The cell's DNA controlled its proteins (through the agency of RNA); and the proteins controlled the synthesis and metabolism of the smaller molecules.

The genetic code

In 1955, Severo Ochoa, at New York University, isolated a bacterial enzyme (RNA polymerase) which was able join the nucleotides A, G, U and C so that they became an RNA strand. One year later, this feat was repeated for DNA by Arthur Kornberg.

With the help of Ochoa's enzyme, it was possible to make synthetic RNA molecules containing only a single nucleotide - for example, one could join uracil molecules into the ribonucleic acid chain, ...U-U-U-U-U-U-... In 1961, Marshall Nirenberg and Heinrich Matthaei used synthetic poly-U as messenger RNA in protein synthesis; and they found that only polyphenylalanine was synthesized. In the same year, Sydney Brenner and Francis Crick reported a series of experiments on mutant strains of the bacteriophage, T4. The experiments of Brenner and Crick showed that whenever a mutation added or deleted either one or two base pairs, the proteins produced by the mutants were highly abnormal and non-functional. However, when the mutation added or subtracted three base pairs, the proteins often were functional. Brenner and Crick concluded that the genetic language

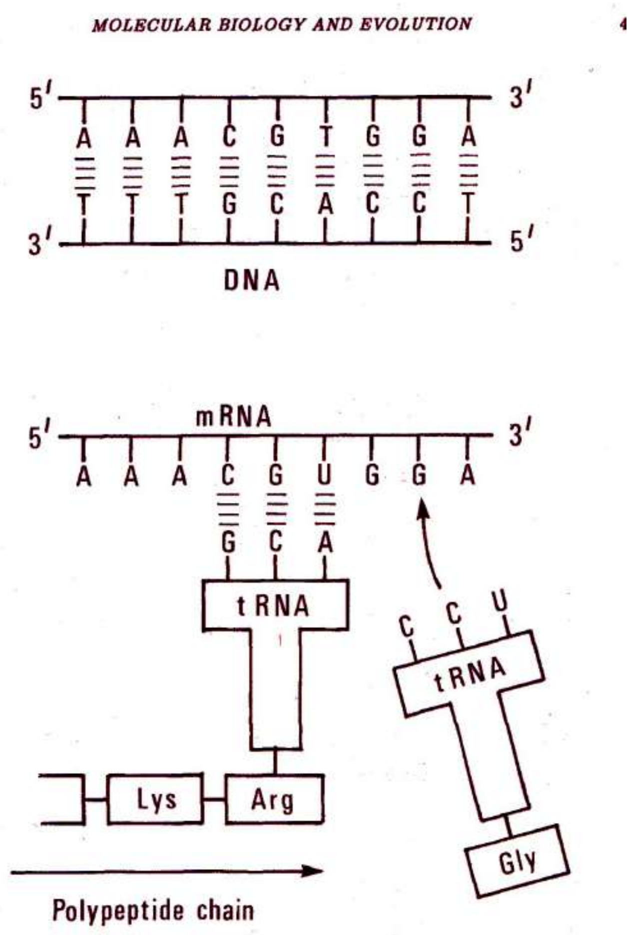


Figure C.1: **Information coded on DNA molecules in the cell nucleus is transcribed to mRNA molecules. The messenger RNA molecules in turn provide information for the amino acid sequence in protein synthesis.**

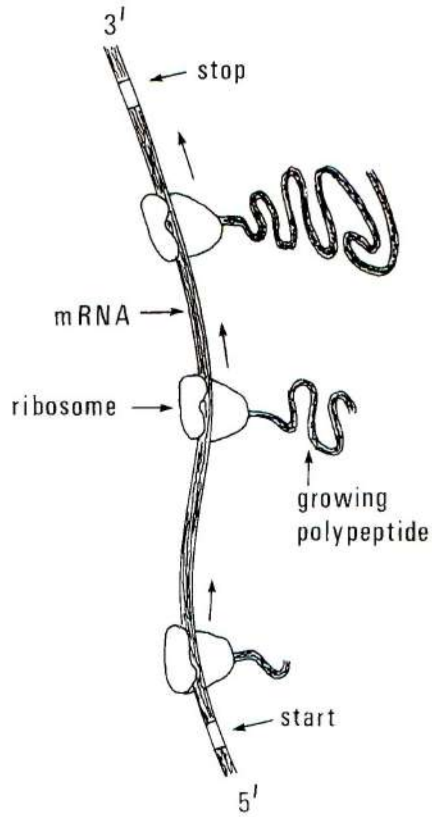


Figure C.2: **mRNA passes through the ribosome like a punched computer tape passing through a tape-reader.**

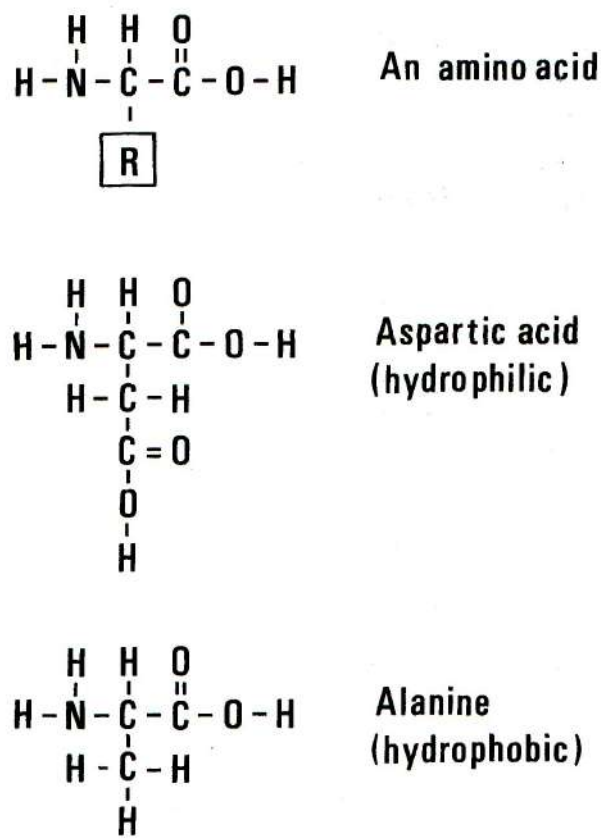


Figure C.3: **This figure shows aspartic acid, whose residue (R) is hydrophilic, contrasted with alanine, whose residue is hydrophobic.**

Table C.1: **The genetic code**

TTT=Phe	TCT=Ser	TAT=Tyr	TGT=Cys
TTC=Phe	TCC=Ser	TAC=Tyr	TGC=Cys
TTA=Leu	TCA=Ser	TAA=Ter	TGA=Ter
TTG=Leu	TGC=Ser	TAG=Ter	TGG=Trp
CTT=Leu	CCT=Pro	CAT=His	CGT=Arg
CTC=Leu	CCC=Pro	CAC=His	CGC=Arg
CTA=Leu	CCA=Pro	CAA=Gln	CGA=Arg
CTG=Leu	CGC=Pro	CAG=Gln	CGG=Arg
ATT=Ile	ACT=Thr	AAT=Asn	AGT=Ser
ATC=Ile	ACC=Thr	AAC=Asn	AGC=Ser
ATA=Ile	ACA=Thr	AAA=Lys	AGA=Arg
ATG=Met	AGC=Thr	AAG=Lys	AGG=Arg
GTT=Val	GCT=Ala	GAT=Asp	GGT=Gly
GTC=Val	GCC=Ala	GAC=Asp	GGC=Gly
GTA=Val	GCA=Ala	GAA=Glu	GGA=Gly
GTG=Val	GGC=Ala	GAG=Glu	GGG=Gly

has three-letter words (codons). With four different "letters", A, T, G and C, this gives sixty-four possible codons - more than enough to specify the twenty different amino acids.

In the light of the phage experiments of Brenner and Crick, Nirenberg and Matthaei concluded that the genetic code for phenylalanine is UUU in RNA and TTT in DNA. The remaining words in the genetic code were worked out by H. Gobind Khorana of the University of Wisconsin, who used other mRNA sequences (such as GUGUGU..., AAGAAGAAG... and GUUGUUGUU...) in protein synthesis. By 1966, the complete genetic code, specifying amino acids in terms of three-base sequences, was known. The code was found to be the same for all species studied, no matter how widely separated they were in form; and this showed that all life on earth belongs to the same family, as postulated by Darwin.

Genetic engineering

In 1970, Hamilton Smith of Johns Hopkins University observed that when the bacterium Haemophilus influenzae is attacked by a bacteriophage (a virus parasitic on bacteria), it can defend itself by breaking down the DNA of the phage. Following up this observation, he introduced DNA from the bacterium E. coli into H. influenzae. Again the foreign DNA was broken down.

Smith had, in fact, discovered the first of a class of bacterial enzymes which came to be called "restriction enzymes" or "restriction nucleases". Almost a hundred other restriction enzymes were subsequently discovered, and each was found to cut DNA at a specific base sequence. Smith's colleague, Daniel Nathans, used the restriction enzymes Hin dll and Hin dill to produce the first "restriction map" of the DNA in a virus.

In 1971 and 1972, Paul Berg, and his co-workers Peter Lobban, Dale Kaiser and David Jackson at Stanford University, developed methods for adding cohesive ends to DNA fragments. Berg and his group used the calf thymus enzyme, terminal transferase, to add short, single-stranded polynucleotide segments to DNA fragments. For example, if they added the single-stranded segment AAAA to one fragment, and TTTT to another, then the two ends joined spontaneously when the fragments were incubated together. In this way Paul Berg and his group made the first recombinant DNA molecules.

The restriction enzyme Eco RI, isolated from the bacterium E. coli, was found to recognize the pattern, GAATTC, in one strand of a DNA molecule, and the complementary pattern, CTTAAG, in the other strand. Instead of cutting both strands in the middle of the six-base sequence, Eco RI was observed to cut both strands between G and A. Thus, each side of the cut was left with a "sticky end" - a five-base single-stranded segment, attached to the remainder of the double-stranded DNA molecule.

In 1972, Janet Mertz and Ron Davis, working at Stanford University, demonstrated that DNA strands cut with Eco RI could be rejoined by means of another enzyme - a DNA ligase. More importantly, when DNA strands from two different sources were cut with Eco RI, the sticky end of one fragment could form a spontaneous temporary bond with the sticky end of the other fragment. The bond could be made permanent by the addition of DNA ligase, even when the fragments came from different sources. Thus, DNA fragments from different organisms could be joined together.

Bacteria belong to a class of organisms (prokaryotes) whose cells do not have a nucleus. Instead, the DNA of the bacterial chromosome is arranged in a large loop. In the early 1950's, Joshua Lederberg had discovered that bacteria can exchange genetic information. He found that a frequently-exchanged gene, the F-factor (which conferred fertility), was not linked to other bacterial genes; and he deduced that the DNA of the F-factor was not physically a part of the main bacterial chromosome. In 1952, Lederberg coined the word "plasmid" to denote any extrachromosomal genetic system. In 1959, it was discovered in Japan that genes for resistance to antibiotics can be exchanged between bacteria; and the name "R-factors" was given to these genes. Like the F-factors, the R-factors did not seem to be part of the main loop of bacterial DNA.

Because of the medical implications of this discovery, much attention was focused on the R-factors. It was found that they are plasmids, small loops of DNA existing inside the bacterial cell but not attached to the bacterial chromosome. Further study showed that, in general, between one percent and three percent of bacterial genetic information is carried by plasmids, which can be exchanged freely even between different species of bacteria.

In the words of the microbiologist, Richard Novick, "Appreciation of the role of plasmids has produced a rather dramatic shift in biologists' thinking about genetics. The traditional view was that the genetic makeup of a species was about the same from one cell to another, and was constant over long periods of time. Now a significant proportion of genetic traits are known to be variable (present in some individual cells or strains, absent in others), labile (subject to frequent loss or gain) and mobile - all because those traits are associated with plasmids or other atypical genetic systems."

In 1973, Herbert Boyer, Stanley Cohen and their co-workers at Stanford University and the University of California carried out experiments in which they inserted foreign DNA segments, cut with Eco RI, into plasmids (also cut with Eco RI). They then resealed the plasmid loops with DNA ligase. Finally, bacteria were infected with the gene-spliced plasmids. The result was a new strain of bacteria, capable of producing an additional protein coded by the foreign DNA segment which had been spliced into the plasmids.

Cohen and Boyer used plasmids containing a gene for resistance to an antibiotic, so that a few gene-spliced bacteria could be selected from a large population by treating the culture with the antibiotic. The selected bacteria, containing both the antibiotic-resistance marker and the foreign DNA, could then be cloned on a large scale; and in this way a foreign gene could be "cloned". The gene-spliced bacteria were chimeras, containing genes from two different species.

The new recombinant DNA techniques of Berg, Cohen and Boyer had revolutionary implications: It became possible to produce many copies of a given DNA segment, so that its base sequence could be determined. With the help of direct DNA-sequencing methods developed by Frederick Sanger and Walter Gilbert, the new cloning techniques could be used for mapping and sequencing genes.

Since new bacterial strains could be created, containing genes from other species, it became possible to produce any protein by cloning the corresponding gene. Proteins of medical importance could be produced on a large scale. Thus, the way was open for the production of human insulin, interferon, serum albumin, clotting factors, vaccines, and protein hormones such as ACTH, human growth factor and leuteinizing hormone.

It also became possible to produce enzymes of industrial and agricultural importance by cloning gene-spliced bacteria. Since enzymes catalyze reactions involving smaller molecules, the production of these substrate molecules through gene-splicing also became possible.

It was soon discovered that the possibility of producing new, transgenic organisms was not limited to bacteria. Gene-splicing was also carried out on higher plants and animals as well as on fungi. It was found that the bacterium Agrobacterium tumefaciens contains a tumor-inducing (Ti) plasmid capable of entering plant cells and producing a crown gall. Genes spliced into the Ti plasmid quite frequently became incorporated in the plant chromosome, and afterwards were inherited in a stable, Mendelian fashion.

Transgenic animals were produced by introducing foreign DNA into embryo-derived stem cells (ES cells). The gene-spliced ES cells were then selected, cultured and introduced into a blastocyst, which afterwards was implanted in a foster-mother. The resulting chimeric animals were bred, and stable transgenic lines selected.

Thus, for the first time, humans had achieved direct control over the process of evolution. Selective breeding to produce new plant and animal varieties was not new - it is one of the oldest techniques of civilization. However, the degree, precision, and speed of intervention which recombinant DNA made possible was entirely new. In the 1970's it became possible to mix the genetic repertoires of different species: The genes of mice and men could be spliced together into new, man-made forms of life!

The Polymerase Chain Reaction

One day in the early 1980's, an American molecular biologist, Kary Mullis, was driving to his mountain cabin with his girl friend. The journey was a long one, and to pass the time, Kary Mullis turned over and over in his mind a problem which had been bothering him: He worked for a California biotechnology firm, and like many other molecular biologists he had been struggling to analyze very small quantities of DNA. Mullis realized that it would be desirable have a highly sensitive way of replicating a given DNA segment - a method much more sensitive than cloning. As he drove through the California mountains, he considered many ways of doing this, rejecting one method after the other as impracticable. Finally a solution came to him; and it seemed so simple that he could hardly believe that he was the first to think of it. He was so excited that he immediately pulled over to the side of the road and woke his sleeping girlfriend to tell her about his idea. Although his girlfriend was not entirely enthusiastic about being wakened from a comfortable sleep to be presented with a lecture on biochemistry, Kary Mullis had in fact invented a technique which was destined to revolutionize DNA technology: the Polymerase Chain Reaction (PCR)[2].

The technique was as follows: Begin with a small sample of the genomic DNA to be analyzed. (The sample may be extremely small - only a few molecules.) Heat the sample to 95 °C to separate the double-stranded DNA molecule into single strands. Suppose that on the long DNA molecule there is a target segment which one wishes to amplify. If the target segment begins with a known sequence of bases on one strand, and ends with a known sequence on the complementary strand, then synthetic "primer" oligonucleotides[3] with these known beginning ending sequences are added in excess. The temperature is then lowered to 50-60 °C, and at the lowered temperature, the "start" primer attaches itself to one DNA strand at the beginning of the target segment, while the "stop" primer becomes attached to the complementary strand at the other end of the target segment. Polymerase (an enzyme which aids the formation of double-stranded DNA) is then added, together with a supply of nucleotides. On each of the original pieces of single-stranded DNA, a new complementary strand is generated with the help of the polymerase. Then the temperature is again raised to 95 °C, so that the double-stranded DNA separates into single strands, and the cycle is repeated.

In the early versions of the PCR technique, the polymerase was destroyed by the high temperature, and new polymerase had to be added for each cycle. However, it was discovered that polymerase from the bacterium Thermus aquaticus would withstand the high temperature. (Thermus aquaticus lives in hot springs.) This discovery greatly simplified the PCR technique. The temperature could merely be cycled between the high and low temperatures, and with each cycle, the population of the target segment doubled, concentrations of primers, deoxynucleotides and polymerase being continuously present.

After a few cycles of the PCR reaction, copies of copies begin to predominate over copies of the original genomic DNA. These copies of copies have a standard length, al-

---

[2] The flash of insight didn't take long, but at least six months of hard work were needed before Mullis and his colleagues could convert the idea to reality.

[3] Short segments of single-stranded DNA.

ways beginning on one strand with the start primer, and ending on that strand with the complement of the stop primer.

Two main variants of the PCR technique are possible, depending on the length of the oligonucleotide primers: If, for example, trinucleotides are used as start and stop primers, they can be expected to match the genomic DNA at many points. In that case, after a number of PCR cycles, populations of many different segments will develop. Within each population, however, the length of the replicated segment will be standardized because of the predominance of copies of copies. When the resulting solution is placed on a damp piece of paper or a gel and subjected to the effects of an electric current (electrophoresis), the populations of different molecular weights become separated, each population appearing as a band. The bands are profiles of the original genomic DNA; and this variant of the PCR technique can be used in evolutionary studies to determine the degree of similarity of the genomic DNA of two species.

On the other hand, if the oligonucleotide primers contain as many as 20 nucleotides, they will be highly specific and will bind only to a particular target sequence of the genomic DNA. The result of the PCR reaction will then be a single population, containing only the chosen target segment. The PCR reaction can be thought of as autocatalytic, and as we shall see in the next section, autocatylitic systems play an important role in modern theories of the origin of life.

Theories of chemical evolution towards the origin of life

The possibility of an era of chemical evolution prior to the origin of life entered the thoughts of Charles Darwin, but he considered the idea to be much too speculative to be included in his published papers and books. However, in February 1871, he wrote a letter to his close friend Sir Joseph Hooker containing the following words:

"It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh what a big if) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts, - light, heat, electricity etc. present, that a protein compound was chemically formed, ready to undergo still more complex changes, at the present day such matter would be instantly devoured, or absorbed, which would not have been the case before living creatures were formed."

The last letter which Darwin is known to have dictated and signed before his death in 1882 also shows that he was thinking about this problem: "You have expressed quite correctly my views", Darwin wrote, "where you said that I had intentionally left the question of the Origin of Life uncanvassed as being altogether ultra vires in the present state of our knowledge, and that I dealt only with the manner of succession. I have met with no evidence that seems in the least trustworthy, in favor of so-called Spontaneous Generation. (However) I believe that I have somewhere said (but cannot find the passage) that the principle of continuity renders it probable that the principle of life will hereafter be shown to be a part, or consequence, of some general law.."

Modern researchers, picking up the problem where Darwin left it, have begun to throw a little light on the problem of chemical evolution towards the origin of life. In the 1930's J.B.S. Haldane in England and A.I. Oparin in Russia put forward theories of an era of chemical evolution prior to the appearance of living organisms.

In 1924 Oparin published a pamphlet on the origin of life. An expanded version of this pamphlet was translated into English and appeared in 1936 as a book entitled *The Origin of Life on Earth*. In this book Oparin pointed out that the time when life originated, conditions on earth were probably considerably different than they are at present: The atmosphere probably contained very little free oxygen, since free oxygen is produced by photosynthesis which did not yet exist. On the other hand, he argued, there were probably large amounts of methane and ammonia in the earth's primitive atmosphere[4]. Thus, before the origin of life, the earth probably had a reducing atmosphere rather than an oxidizing one. Oparin believed that energy-rich molecules could have been formed very slowly by the action of light from the sun. On the present-day earth, bacteria quickly consume energy-rich molecules, but before the origin of life, such molecules could have accumulated, since there were no living organisms to consume them. (This observation is similar to the remark made by Darwin in his 1871 letter to Hooker.)

The first experimental work in this field took place in 1950 in the laboratory of Melvin Calvin at the University of California, Berkeley. Calvin and his co-workers wished to determine experimentally whether the primitive atmosphere of the earth could have been converted into some of the molecules which are the building-blocks of living organisms. The energy needed to perform these conversions they imagined to be supplied by volcanism, radioactive decay, ultraviolet radiation, meteoric impacts, or by lightning strokes.

The earth is thought to be approximately 4.6 billion years old. At the time when Calvin and his co-workers were performing their experiments, the earth's primitive atmosphere was believed to have consisted primarily of hydrogen, water, ammonia, methane, and carbon monoxide, with a little carbon dioxide. A large quantity of hydrogen was believed to have been initially present in the primitive atmosphere, but it was thought to have been lost gradually over a period of time because the earth's gravitational attraction is too weak to effectively hold such a light and rapidly-moving molecule. However, Calvin and his group assumed sufficient hydrogen to be present to act as a reducing agent. In their 1950 experiments they subjected a mixture of hydrogen and carbon dioxide, with a catalytic amount of Fe^{2+}, to bombardment by fast particles from the Berkeley cyclotron. Their experiments resulted in a good yield of formic acid and a moderate yield of formaldehyde. (The fast particles from the cyclotron were designed to simulate an energy input from radioactive decay on the primitive earth.)

Two years later, Stanley Miller, working in the laboratory of Harold Urey at the University of Chicago, performed a much more refined experiment of the same type. In Miller's experiment, a mixture of the gases methane, ammonia, water and hydrogen was subjected to an energy input from an electric spark. Miller's apparatus was designed so that the gases were continuously circulated, passing first through the spark chamber, then through

[4] It is now believed that the main constituents of the primordial atmosphere were carbon dioxide, water, nitrogen, and a little methane.

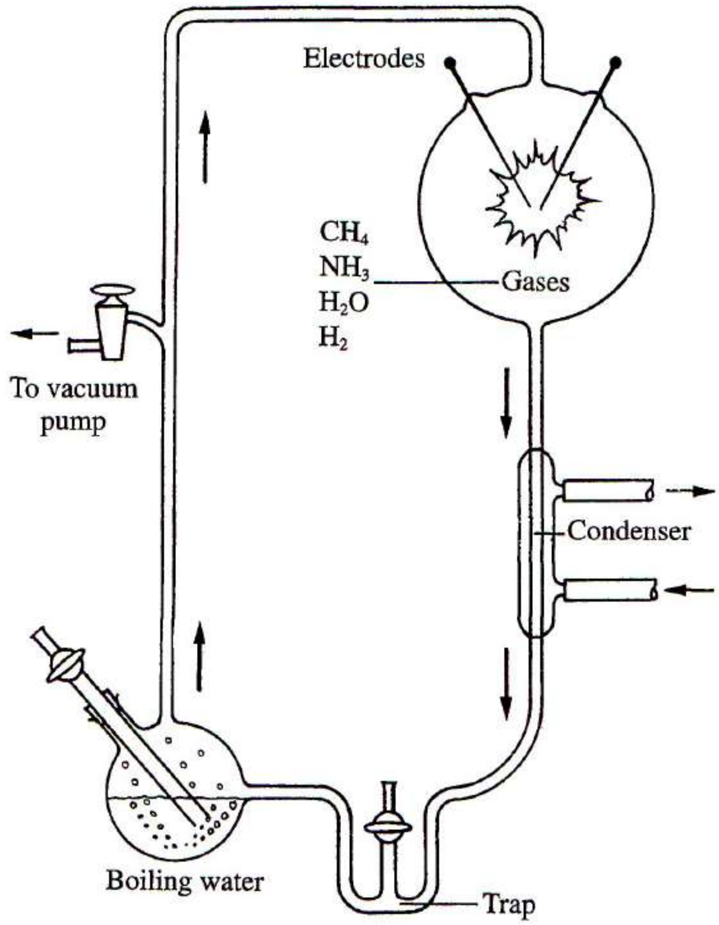


Figure C.4: **Miller's apparatus.**

a water trap which removed the non-volatile water soluble products, and then back again through the spark chamber, and so on. The resulting products are shown as a function of time in Figure 3.5.

The Miller-Urey experiment produced many of the building-blocks of living organisms, including glycine, glycolic acid, sarcosine, alanine, lactic acid, N-methylalanine, β-alanine, succinic acid, aspartic acid, glutamic acid, iminodiacetic acid, iminoacetic-propionic acid, formic acid, acetic acid, propionic acid, urea and N-methyl urea[5]. Another major product was hydrogen cyanide, whose importance as an energy source in chemical evolution was later emphasized by Calvin.

The Miller-Urey experiment was repeated and extended by the Ceylonese-American biochemist Cyril Ponnamperuma and by the American expert in planetary atmospheres,

[5] The chemical reaction that led to the formation of the amino acids that Miller observed was undoubtedly the Strecker synthesis: $HCN + NH_3 + RC{=}O + H_2O \rightarrow RC(NH_2)COOH$.

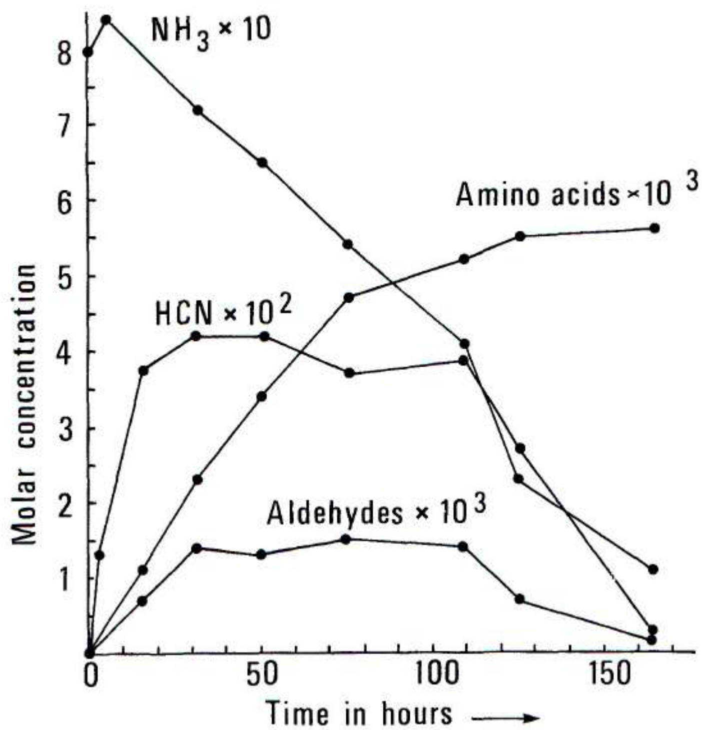


Figure C.5: **Products as a function of time in the Miller-Urey experiment.**

Carl Sagan. They showed that when phosphorus is made available, then in addition to amino acids, the Miller-Urey experiment produces not only nucleic acids of the type that join together to form DNA, but also the energy-rich molecule ATP (adenosine triphosphate). ATP is extremely important in biochemistry, since it is a universal fuel which drives chemical reactions inside present-day living organisms.

Further variations on the Miller-Urey experiment were performed by Sydney Fox and his co-workers at the University of Miami. Fox and his group showed that amino acids can be synthesized from a primitive atmosphere by means of a thermal energy input, and that in the presence of phosphate esters, the amino acids can be thermally joined together to form polypeptides. However, some of the peptides produced in this way were cross linked, and hence not of biological interest.

In 1969, Melvin Calvin published an important book entitled *Chemical Evolution; Molecular Evolution Towards the Origin of Living Systems on Earth and Elsewhere*. In this book, Calvin reviewed the work of geochemists showing the presence in extremely ancient rock formations of molecules which we usually think of as being produced only by living organisms. He then discussed experiments of the Miller-Urey type - experiments simulating the first step in chemical evolution. According to Calvin, not only amino acids but also the bases adenine, thymine, guanine, cytosine and uracil, as well as various sugars, were probably present in the primitive ocean in moderate concentrations, produced from the primitive atmosphere by the available energy inputs, and not broken down because no organisms were present.

The next steps visualized by Calvin were dehydration reactions in which the building blocks were linked together into peptides, polynucleotides, lipids and porphyrins. Such dehydration reactions are in a thermodynamically uphill direction. In modern organisms, they are driven by a universally-used energy source, the high-energy phosphate bond of adenosine triphosphate (ATP). Searching for a substance present in the primitive ocean which could have driven the dehydrations, Calvin and his coworkers experimented with hydrogen cyanide (HC=N), and from the results of these experiments they concluded that the energy stored in the carbon-nitrogen triple bond of HC=N could indeed have driven the dehydration reactions necessary for polymerization of the fundamental building blocks. However, later work made it seem improbable that peptides could be produced from cyanide mixtures.

In Chemical Evolution, Calvin introduced the concept of autocatalysis as a mechanism for molecular selection, closely analogous to natural selection in biological evolution. Calvin proposed that there were a few molecules in the ancient oceans which could catalyze the breakdown of the energy-rich molecules present into simpler products. According to Calvin's hypothesis, in a very few of these reactions, the reaction itself produced more of the catalyst. In other words, in certain cases the catalyst not only broke down the energy-rich molecules into simpler products but also catalyzed their own synthesis. These autocatalysts, according to Calvin, were the first systems which might possibly be regarded as living organisms. They not only "ate" the energy-rich molecules but they also reproduced - i.e., they catalyzed the synthesis of molecules identical with themselves.

Autocatalysis leads to a sort of molecular natural selection, in which the precursor molecules and the energy-rich molecules play the role of "food", and the autocatalytic systems compete with each other for the food supply. In Calvin's picture of molecular evolution, the most efficient autocatalytic systems won this competition in a completely Darwinian way. These more efficient autocatalysts reproduced faster and competed more successfully for precursors and for energy-rich molecules. Any random change in the direction of greater efficiency was propagated by natural selection.

What were these early autocatalytic systems, the forerunners of life? Calvin proposed several independent lines of chemical evolution, which later, he argued, joined forces. He visualized the polynucleotides, the polypeptides, and the metallo-porphyrins as originally having independent lines of chemical evolution. Later, he argued, an accidental union of these independent autocatalysts showed itself to be a still more efficient autocatalytic system. He pointed out in his book that "autocatalysis" is perhaps too strong a word. One should perhaps speak instead of "reflexive catalysis" , where a molecule does not necessarily catalyze the synthesis of itself, but perhaps only the synthesis of a precursor. Like autocatalysis, reflexive catalysis is capable of exhibiting Darwinian selectivity.

The theoretical biologist, Stuart Kauffman, working at the Santa Fe Institute, has constructed computer models for the way in which the components of complex systems of reflexive catalysts may have been linked together. Kauffman's models exhibit a surprising tendency to produce orderly behavior even when the links are randomly programmed.

In 1967 and 1968, C. Woese, F.H.C. Crick and L.E. Orgel proposed that there may have been a period of chemical evolution involving RNA alone, prior to the era when DNA, RNA and proteins joined together to form complex self-reproducing systems. In the early 1980's, this picture of an "RNA world" was strengthened by the discovery (by Thomas R. Cech and Sydney Altman) of RNA molecules which have catalytic activity.

Today experiments aimed at throwing light on chemical evolution towards the origin of life are being performed in the laboratory of the Nobel Laureate geneticist Jack Sjostak at Harvard Medical School. The laboratory is trying to build a synthetic cellular system that undergoes Darwinian evolution.

In connection with autocatalytic systems, it is interesting to think of the polymerase chain reaction, which we discussed above. The target segment of DNA and the polymerase together form an autocatalytic system. The "food" molecules are the individual nucleotides in the solution. In the PCR system, a segment of DNA reproduces itself with an extremely high degree of fidelity. One can perhaps ask whether systems like the PCR system can have been among the forerunners of living organisms. The cyclic changes of temperature needed for the process could have been supplied by the cycling of water through a hydrothermal system. There is indeed evidence that hot springs and undersea hydrothermal vents may have played an important role in chemical evolution towards the origin of life. We will discuss this evidence in the next section.

Throughout this discussion of theories of chemical evolution, and the experiments which have been done to support these theories, energy has played a central role. None of the transformations discussed above could have taken place without an energy source, or to be more precise, they could not have taken place without a source of free energy.

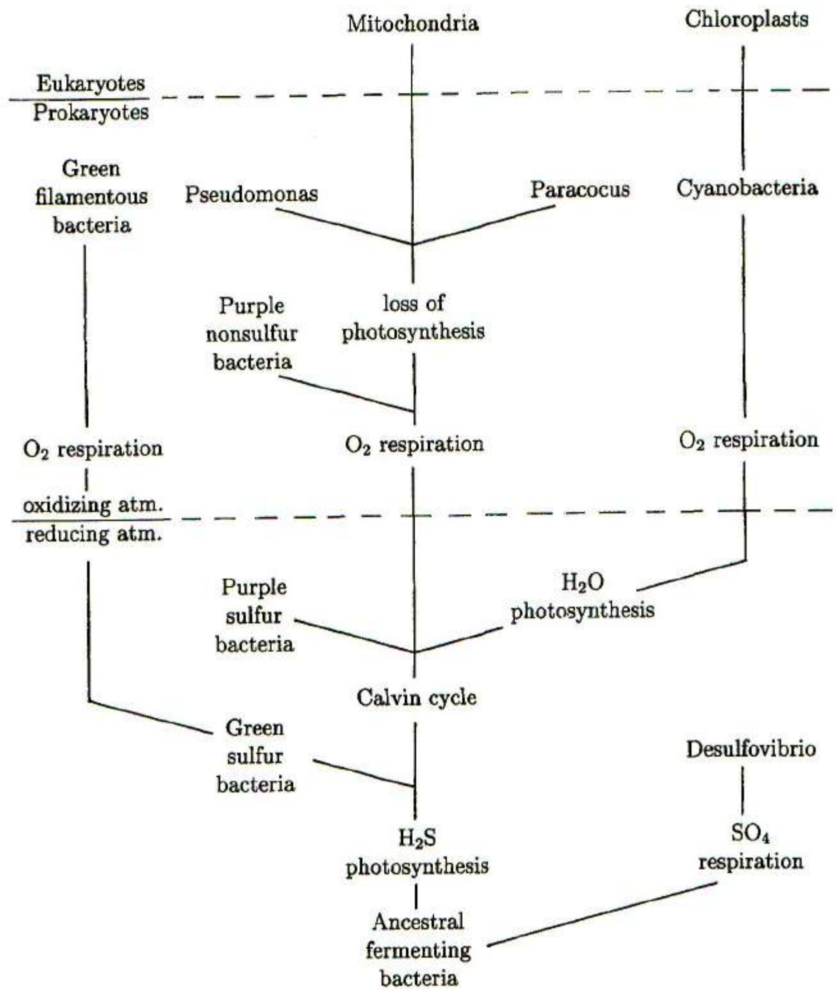


Figure C.6: **Evolutionary relationships established by Dickerson and coworkers by comparing the amino acid sequences of Cytochrome C from various species.**

Molecular evidence establishing family trees in evolution

Starting in the 1970's, the powerful sequencing techniques developed by Sanger and others began to be used to establish evolutionary trees. The evolutionary closeness or distance of two organisms could be estimated from the degree of similarity of the amino acid sequences of their proteins, and also by comparing the base sequences of their DNA and RNA. One of the first studies of this kind was made by R.E. Dickerson and his coworkers, who studied the amino acid sequences in Cytochrome C, a protein of very ancient origin which is involved in the "electron transfer chain" of respiratory metabolism. Some of the results of Dickerson's studies are shown in Figure 3.6.

Comparison of the base sequences of RNA and DNA from various species proved to be even more powerful tool for establishing evolutionary relationships. Figure 3.7 shows the

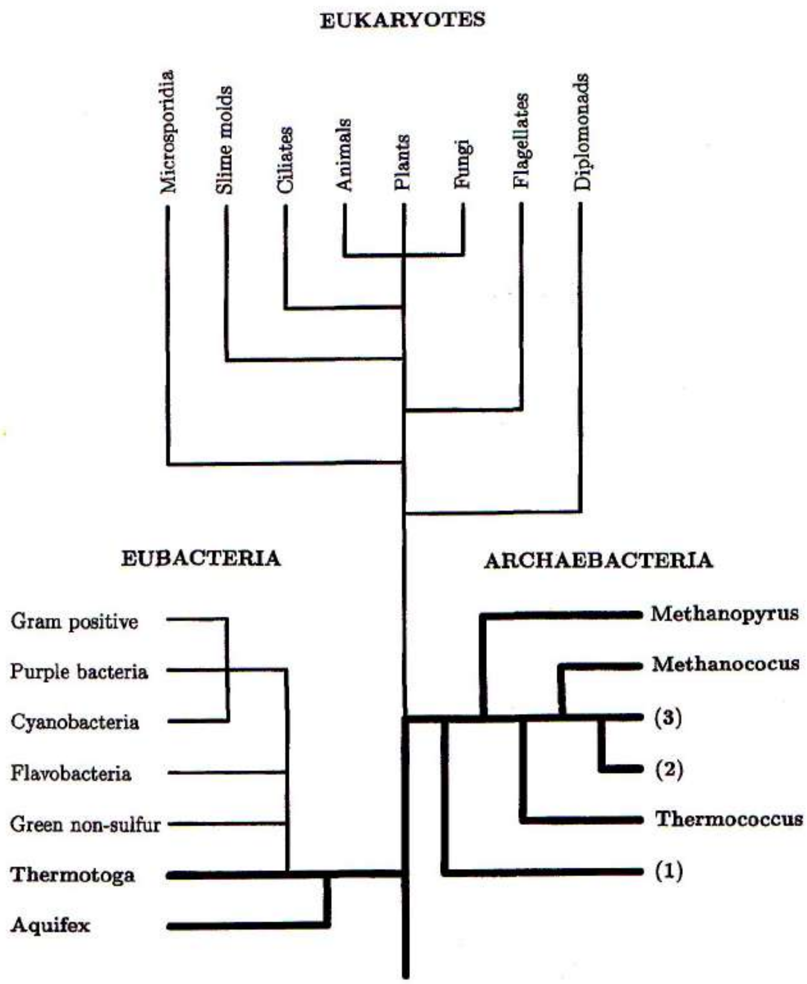


Figure C.7: **This figure shows the universal phylogenetic tree, established by the work of Woese, Iwabe et al. Hyperthermophiles are indicated by bold lines and by bold type.**

universal phylogenetic tree established in this way by Iwabe, Woese and their coworkers.[6] In Figure 3.7, all presently living organisms are divided into three main kingdoms, Eukaryotes, Eubacteria, and Archaebacteria. Carl Woese, who proposed this classification on the basis of comparative sequencing, wished to call the three kingdoms "Eucarya, Bacteria and Archaea". However, the most widely accepted terms are the ones shown in capital letters on the figure. Before the comparative RNA sequencing work, which was performed on the ribosomes of various species, it had not been realized that there are two types of bacteria, so markedly different from each other that they must be classified as belonging to separate kingdoms. One example of the difference between archaebacteria and eubacteria is that the former have cell membranes which contain ether lipids, while the latter have ester lipids in their cell membranes. Of the three kingdoms, the eubacteria and the archaebacteria are "prokaryotes", that is to say, they are unicellular organisms having no cell nucleus. Most of the eukaryotes, whose cells contain a nucleus, are also unicellular, the exceptions being plants, fungi and animals.

One of the most interesting features of the phylogenetic tree shown in Figure 3.7 is that the deepest branches - the organisms with shortest pedigrees - are all hyperthermophiles, i.e. they live in extremely hot environments such as hot springs or undersea hydrothermal vents. The shortest branches represent the most extreme hyperthermophiles. The group of archaebacteria indicated by (1) in the figure includes *Thermofilum, Thermoproteus, Pyrobaculum, Pyrodictium, Desulfurococcus*, and *Sulfolobus* - all hypothermophiles[7]. Among the eubacteria, the two shortest branches, Aquifex and Thermatoga are both hyperthermophiles[8]

The phylogenetic evidence for the existence of hyperthermophiles at a very early stage of evolution lends support to a proposal put forward in 1988 by the German biochemist Günter Wächterhäuser. He proposed that the reaction for pyrite formation,

$$FeS + H_2S \rightarrow FeS_2 + 2H + +2e^-$$

which takes place spontaneously at high temperatures, supplied the energy needed to drive the first stages of chemical evolution towards the origin of life. Wächterhäuser pointed out that the surface of the mineral pyrite (FeS_2) is positively charged, and he proposed that, since the immediate products of carbon-dioxide fixation are negatively charged, they would be attracted to the pyrite surface. Thus, in Wächterhäuser's model, pyrite formation not only supplied the reducing agent needed for carbon-dioxide fixation, but also the pyrite surface aided the process. Wächterhäuser further proposed an archaic autocatylitic carbon-dioxide fixation cycle, which he visualized as resembling the reductive citric acid cycle

[6] "Phylogeny" means "the evolutionary development of a species". "Ontogeny" means "the growth and development an individual, through various stages, for example, from fertilized egg to embryo, and so on." Ernst Haeckel, a 19th century follower of Darwin, observed that, in many cases, "ontogeny recapitulates phylogeny."

[7] Group (2) in Figure 3.7 includes *Methanothermus*, which is hyperthermophilic, and Methanobacterium, which is not. Group (3) includes *Archaeoglobus*, which is hyperthermophilic, and Halococcus, Halobacterium, Methanoplanus, Methanospirilum, and Methanosarcina, which are not.

[8] Thermophiles are a subset of the larger group of extremophiles.

found in present-day organisms, but with all reducing agents replaced by FeS + H_2S, with thioester activation replaced by thioacid activation, and carbonyl groups replaced by thioenol groups. The interested reader can find the details of Wächterhäuser's proposals in his papers, which are listed at the end of this chapter.

A similar picture of the origin of life has been proposed by Michael J. Russell and Alan J. Hall in 1997. In this picture "...(i) life emerged as hot, reduced, alkaline, sulphide-bearing submarine seepage waters interfaced with colder, more oxidized, more acid, $Fe^{2+} >> Fe^{3+}$-bearing water at deep (*ca.* 4km) floors of the Hadian ocean *ca.* 4 Gyr ago; (ii) the difference in acidity, temperature and redox potential provided a gradient of pH (*ca.* 4 units), temperature (*ca.* 60°C) and redox potential (*ca.* 500 mV) at the interface of those waters that was sustainable over geological time-scales, providing the continuity of conditions conducive to organic chemical reactions needed for the origin of life..." [9]. Russell, Hall and their coworkers also emphasize the role that may have been played by spontaneously-formed 3-dimensional mineral chambers (bubbles). They visualize these as having prevented the reacting molecules from diffusing away, thus maintaining high concentrations.

Table 3.2 shows the energy-yielding reactions which drive the metabolisms of some organisms which are of very ancient evolutionary origin. All the reactions shown in the table make use of H_2, which could have been supplied by pyrite formation at the time when the organisms evolved. All these organisms are lithoautotrophic, a word which requires some explanation: A heterotrophic organism is one which lives by ingesting energy-rich organic molecules which are present in its environment. By contrast, an autotrophic organism ingests only inorganic molecules. The lithoautotrophs use energy from these inorganic molecules, while the metabolisms of photoautotrophs are driven by energy from sunlight.

Evidence from layered rock formations called "stromatolites", produced by colonies of photosynthetic bacteria, show that photoautotrophs (or phototrophs) appeared on earth at least 3.5 billion years ago. The geological record also supplies approximate dates for other events in evolution. For example, the date at which molecular oxygen started to become abundant in the earth's atmosphere is believed to have been 2.0 billion years ago, with equilibrium finally being established 1.5 billion years in the past. Multi-cellular organisms appeared very late on the evolutionary and geological time-scale - only 600 million years ago. By collecting such evidence, the Belgian cytologist Christian de Duve has constructed the phylogenetic tree shown in Figure 3.8, showing branching as a function of time. One very interesting feature of this tree is the arrow indicating the transfer of "endosymbionts" from the eubacteria to the eukaryotes. In the next section, we will look in more detail at this important event, which took place about 1.8 billion years ago.

[9]See W. Martin and M.J. Russell, *On the origins of cells: a hypothesis for the evolutionary transitions from abiotic geochemistry to chemoautotrophic prokaryotes, and from prokaryotes to nucleated cells*, Philos. Trans. R. Soc. Lond. B Biol. Sci., *358*, 59-85, (2003).

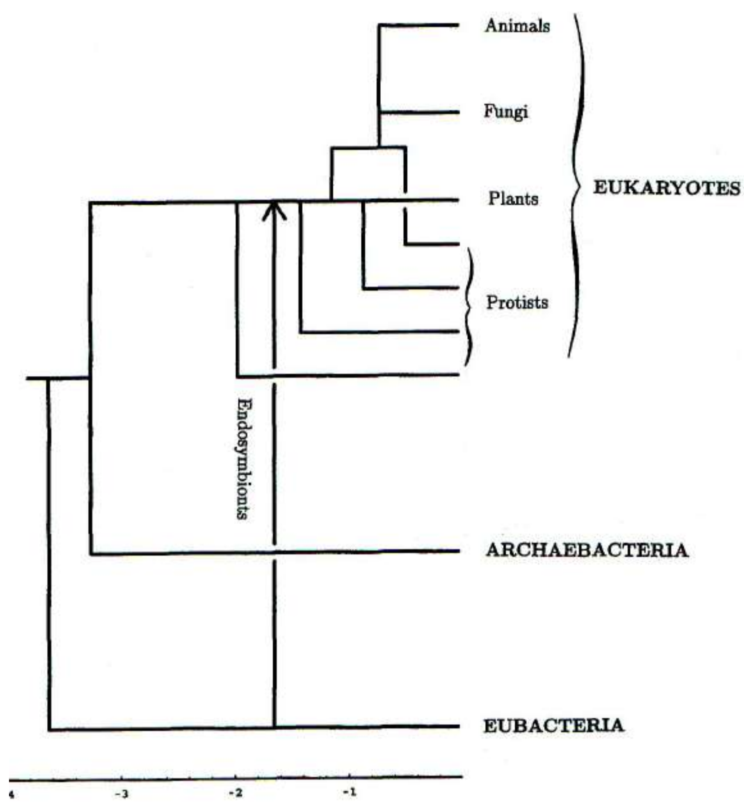


Figure C.8: Branching of the universal phylogenetic tree as a function of time. "Protists" are unicellular eukaryotes.

Table C.2: **Energy-yielding reactions of some lithoautotrophic hyperthermophiles. (After K.O. Setter)**

Energy-yielding reaction	Genera
$4H_2+CO_2 \rightarrow CH_4+2H_2O$	Methanopyrus, Methanothermus, Methanococcus
$H_2+S^\circ \rightarrow H_2S$	Pyrodictium, Thermoproteus, Pyrobaculum, Acidianus, Stygiolobus
$4H_2+H_2SO_4 \rightarrow H_2S+4H_2O$	Archaeoglobus

Symbiosis

The word “symbiosis” is derived from Greek roots meaning “living together”. It was coined in 1877 by the German botanist Albert Bernard Frank. By that date, it had become clear that lichens are composite organisms involving a fungus and an alga; but there was controversy concerning whether the relationship was a parasitic one. Was the alga held captive and exploited by the fungus? Or did the alga and the fungus help each other, the former performing photosynthesis, and the latter leeching minerals from the lichen’s environment? In introducing the word “symbiosis” (in German, “Symbiotismus”), Prank remarked that “We must bring all the cases where two different species live on or in one another under a comprehensive concept which does not consider the role which the two individuals play but is based on the mere coexistence, and for which the term symbiosis is to be recommended.” Thus the concept of symbiosis, as defined by Frank, included all intimate relationships between two or more species, including parasitism at one extreme and “mutualism” at the other. However, as the word is used today, it usually refers to relationships which are mutually beneficial.

Charles Darwin himself had been acutely aware of close and mutually beneficial relationships between organisms of different species. For example, in his work on the fertilization of flowers,he had demonstrated the way in which insects and plants can become exquisitely adapted to each other’s needs. However, T.H. Huxley, “Darwin’s bulldog”, emphasized competition as the predominant force in evolution. “The animal world is on about the same level as a gladiator’s show”, Huxley wrote in 1888, “The creatures are fairly well treated and set to fight - whereby the strongest, the swiftest and the cunningest live to fight another day. The spectator has no need to turn his thumbs down, as no quarter is given." The view of nature as a sort of "gladiator's contest" dominated the mainstream of evolutionary thought far into the 20th century; but there was also a growing body of opinion which held that symbiosis could be an extremely important mechanism for the generation of new species.

Among the examples of symbiosis studied by Frank were the nitrogen-fixing bacteria living in nodules on the roots of legumes, and the mycorrhizal fungi which live on the roots of forest trees such as oaks, beech and conifers. Frank believed that the mycorrhizal fungi aid in the absorption of nutrients. He distinguished between "ectotrophic" fungi, which form sheaths around the root fibers, and "endotrophic" fungi, which penetrate the root cells. Other examples of symbiosis studied in the 19th century included borderline cases between plants and animals, for ex- ample, paramecia, sponges, hydra, planarian worms and sea anemones, all of which frequently contain green bodies capable of performing photosynthesis.

Writing in 1897, the American lichenologist Albert Schneider prophesied that "future studies may demonstrate that.., plasmic bodies (within the eukaryote cell), such as chlorophyll granules, leucoplastids, chromoplastids, chromosomes, centrosomes, nucleoli, etc., are perhaps symbionts comparable to those in less highly specialized symbiosis. Reinke expresses the opinion that it is not wholly unreasonable to suppose that some highly skilled scientist of the future may succeed in cultivating chlorophyll-bodies in artificial media."

19th century cytologists such as Robert Altman, Andreas Schimper and A. Benda focused attention on the chlorophyll-bodies of plants, which Schimper named chloroplasts, and on another type of subcellular granule, present in large numbers in all plant and animal cells, which Benda named mitochondria, deriving the name from the Greek roots mitos (thread) and chrondos (granule). They observed that these bodies seemed to reproduce themselves within the cell in very much the manner that might be expected if they were independent organisms. Schimper suggested that chloroplasts are symbionts, and that green plants owe their origin to a union of a colorless unicellular organism with a smaller chlorophyll-containing species.

The role of symbiosis in evolution continued to be debated in the 20th century. Mitochondria were shown to be centers of respiratory metabolism; and it was discovered that both mitochondria and chloroplasts contain their own DNA. However, opponents of their symbiotic origin pointed out that mitochondria alone cannot synthesize all their own proteins: Some mitochondrial proteins require information from nuclear DNA. The debate was finally settled in the 1970's, when comparative sequencing of ribosomal RNA in the laboratories of Carl Woese, W. Ford Doolittle and Michael Gray showed conclusively that both chloroplasts and mitochondria were originally endosymbionts. The ribosomal RNA sequences showed that chloroplasts had their evolutionary root in the cyanobacteria, a species of eubacteria, while mitochondria were traced to a group of eubacteria called the alpha-proteobacteria. Thus the evolutionary arrow leading from the eubacteria to the eukaryotes can today be drawn with confidence, as in Figure 3.8.

Cyanobacteria are bluish photosynthetic bacteria which often become linked to one another so as to form long chains. They can be found today growing in large colonies on seacoasts in many parts of the world, for example in Baja California on the Mexican coast. The top layer of such colonies consists of the phototrophic cyanobacteria, while the organisms in underlying layers are heterotrophs living off the decaying remains of the cyanobacteria. In the course of time, these layered colonies can become fossilized, and they are the source of the layered rock formations called stromatolites (discussed above). Geological dating of ancient stromatolites has shown that cyanobacteria must have originated at least 3.5 billion years ago.

Cyanobacteria contain two photosystems, each making use of a different type of chlorophyll. Photosystem I, which is thought to have evolved first, uses the energy of light to draw electrons from inorganic compounds, and sometimes also from organic compounds (but never from water). Photosystem II, which evolved later, draws electrons from water. Hydrogen derived from the water is used to produce organic compounds from carbon-dioxide, and molecular oxygen is released into the atmosphere. Photosystem II never appears alone. In all organisms which possess it, Photosystem II is coupled to Photosystem I, and together the two systems raise electrons to energy levels that are high enough to drive all the processes of metabolism. Dating of ancient stromatolites makes it probable that cyanobacteria began to release molecular oxygen into the earth's atmosphere at least 3.5 billion years ago; yet from other geological evidence we know that it was only 2 billion years ago that the concentration of molecular oxygen began to rise, equilibrium being reached 1.5 billion years ago. It is believed that ferrous iron, which at one time was very abundant, initially absorbed the photosynthetically produced oxygen. This resulted in the time-lag, as well as the ferrous-ferric mixture of iron which is found in the mineral magnetite.

When the concentrations of molecular oxygen began to rise in earnest, most of the unicellular microorganisms living at the time found themselves in deep trouble, faced with extinction, because for them oxygen was a deadly poison; and very many species undoubtedly perished. However, some of the archaebacteria retreated to isolated anaerobic niches where we find them today, while others found ways of detoxifying the poisonous oxygen. Among the eubacteria, the ancestors of the alpha-proteobacteria were particularly good at dealing with oxygen and even turning it to advantage: They developed the biochemical machinery needed for respiratory metabolism.

Meanwhile, during the period between 3.5 and 2.0 billion years before the present, an extremely important evolutionary development had taken place: Branching from the archaebacteria, a line of large[10] heterotrophic unicellular organisms had evolved. They lacked rigid cell walls, and they could surround smaller organisms with their flexible outer membrane, drawing the victims into their interiors to be digested. These new heterotrophs were the ancestors of present-day eukaryotes, and thus they were the ancestors of all multicellular organisms.

Not only are the cells of present-day eukaryotes very much larger than the cells of archaebacteria and eubacteria; their complexity is also astonishing. Every eukaryote cell contains numerous intricate structures: a nucleus, cytoskeleton, Golgi apparatus, endoplas-

[10] not large in an absolute sense, but large in relation to the prokaryotes

mic reticulum, mitochondria, peroxisomes, chromosomes, the complex structures needed for mitotic cell division, and so on. Furthermore, the genomes of eykaryotes contain very much more information than those of prokaryotes. How did this huge and relatively sudden increase in complexity and information content take place? According to a growing body of opinion, symbiosis played an important role in this development.

The ancestors of the eukaryotes were in the habit of drawing the smaller prokaryotes into their interiors to be digested. It seems likely that in a few cases the swallowed prokaryotes resisted digestion, multiplied within the host, were transmitted to future generations when the host divided, and conferred an evolutionary advantage, so that the result was a symbiotic relationship. In particular, both mitochondria and chloroplasts have definitely been proved to have originated as endosymbionts. It is easy to understand how the photosynthetic abilities of the chloroplasts (derived from cyanobacteria) could have conferred an advantage to their hosts, and how mitochondria (derived from alpha-proteobacteria) could have helped their hosts to survive the oxygen crisis. The symbiotic origin of other sub-cellular organelles is less well understood and is currently under intense investigation.

If we stretch the definition of symbiosis a little, we can make the concept include cooperative relationships between organisms of the same species. For example, cyanobacteria join together to form long chains, and they live together in large colonies which later turn into stromatolites. Also, some eubacteria have a mechanism for sensing how many of their species are present, so that they know, like a wolf pack, when it is prudent to attack a larger organism. This mechanism, called "quorum sensing", has recently attracted much attention among medical researchers.

The cooperative behavior of a genus of unicellular eukaryotes called slime molds is particularly interesting because it gives us a glimpse of how multicellular organisms may have originated. The name of the slime molds is misleading, since they are not fungi, but heterotrophic protists similar to amoebae. Under ordinary circumstances, the individual cells wander about independently searching for food, which they draw into their interiors and digest, a process called "phagocytosis". However, when food is scarce, they send out a chemical signal of distress. Researchers have analyzed the molecule which expresses slime mold unhappiness, and they have found it to be cyclic adenosine monophosphate (cAMP). At this signal, the cells congregate and the mass of cells begins to crawl, leaving a slimy trail. As it crawls, the community of cells gradually develops into a tall stalk, surmounted by a sphere - the "fruiting body". Inside the sphere, spores are produced by a sexual process. If a small animal, for example a mouse, passes by, the spores may adhere to its coat; and in this way they may be transported to another part of the forest where food is more plentiful.

Thus slime molds represent a sort of missing link between unicellular and multicellular or organisms. Normally the cells behave as individualists, wandering about independently, but when challenged by a shortage of food, the slime mold cells join together into an entity which closely resembles a multicellular organism. The cells even seem to exhibit altruism, since those forming the stalk have little chance of survival, and yet they are willing to perform their duty, holding up the sphere at the top so that the spores will survive and carry the genes of the community into the future. We should especially notice the fact that the cooperative behavior of the slime mold cells is coordinated by chemical signals.

Sponges are also close to the borderline which separates unicellular eukaryotes (protists) from multicellular organisms, but they are just on the other side of the border. Normally the sponge cells live together in a multicellular community, filtering food from water. However, if a living sponge is forced through a very fine cloth, it is possible to separate the cells from each other. The sponge cells can live independently for some time; but if many of them are left near to one another, they gradually join together and form themselves into a new sponge, guided by chemical signals. In a refinement of this experiment, one can take two living sponges of different species, separate the cells by passing the sponges through a fine cloth, and afterwards mix all the separated cells together. What happens next is amazing: The two types of sponge cells sort themselves out and become organized once more into two sponges - one of each species.

Slime molds and sponges hint at the genesis of multicellular organisms, whose evolution began approximately 600 million years ago. Looking at the slime molds and sponges, we can imagine how it happened. Some unicellular organisms must have experienced an enhanced probability of survival when they lived as colonies. Cooperative behavior and division of labor within the colonies were rewarded by the forces of natural selection, with the selective force acting on the entire colony of cells, rather than on the individual cell. This resulted in the formation of cellular societies and the evolution of mechanisms for cell differentiation. The division of labor within cellular societies (i.e., differentiation) came to be coordinated by chemical signals which affected the transcription of genetic information and the synthesis of proteins. Each cell within a society of cells possessed the entire genome characteristic of the colony, but once a cell had been assigned its specific role in the economy of the society, part of the information became blocked - that is, it was not expressed in the function of that particular cell. As multicellular organisms evolved, the chemical language of intercellular communication became very much more complex and refined. We will discuss the language of intercellular communication in more detail in a later section.

Geneticists have become increasingly aware that symbiosis has probably played a major role in the evolution of multicellular organisms. We mentioned above that, by means of genetic engineering techniques, transgenic plants and animals can be produced. In these chimeras, genetic material from a foreign species is incorporated into the chromosomes, so that it is inherited in a stable, Mendelian fashion. J.A. Shapiro, one of whose articles is referenced at the end of this chapter, believes that this process also occurs in nature, so that the conventional picture of evolutionary family trees needs to be corrected. Shapiro believes that instead of evolutionary trees, we should perhaps think of webs or networks.

For example, it is tempting to guess that symbiosis may have played a role in the development of the visual system of vertebrates. One of the archaebacteria, the purple halobacterium halobium (recently renamed halobacterium salinarum), is able to perform photosynthesis by means of a protein called bacterial rhodopsin, which transports hydrogen ions across the bacterial membrane. This protein is a near chemical relative of rhodopsin, which combines with a carotinoid to form the "visual purple" used in the vertebrate eye. It is tempting to think that the close similarity of the two molecules is not just a coincidence, and that vertebrate vision originated in a symbiotic relationship between the photosynthetic halobacterium and an aquatic ancestor of the vertebrates, the host being able to sense when the halobacterium was exposed to light and therefore transporting hydrogen ions across its cell membrane.

In this chapter, we have looked at the flow of energy and information in the origin and evolution of life on earth. We have seen how energy-rich molecules were needed to drive the first steps in the origin of life, and how during the evolutionary process, information was preserved, transmitted, and shared between increasingly complex organisms, the whole process being driven by an input of energy. In the next chapter, we will look closely at the relationships between energy and information.

C.2 Life elsewhere in the universe

On December 18, 2017, scientists from the University of California published an article in *Science News* entitled *Ancient fossil microorganisms indicate that life in the universe is common*. According to the article:

"A new analysis of the oldest known fossil microorganisms provides strong evidence to support an increasingly widespread understanding that life in the universe is common.

"The microorganisms, from Western Australia, are 3.465 billion years old. Scientists from UCLA and the University of Wisconsin-Madison report today in the journal Proceedings of the National Academy of Sciences that two of the species they studied appear to have performed a primitive form of photosynthesis, another apparently produced methane gas, and two others appear to have consumed methane and used it to build their cell walls.

"The evidence that a diverse group of organisms had already evolved extremely early in the Earth's history, combined with scientists' knowledge of the vast number of stars in the universe and the growing understanding that planets orbit so many of them, strengthens the case for life existing elsewhere in the universe because it would be extremely unlikely that life formed quickly on Earth but did not arise anywhere else."

Suggestions for further reading

1. H. Lodish, A. Berk, S.L. Zipursky, P. Matsudaira, D. Baltimore, and J. Darnell, *Molecular Cell Biology, 4th Edition*, W.H. Freeman, New York, (2000).
2. Lily Kay, *Who Wrote the Book of Life? A History of the Genetic Code*, Stanford University Press, Stanford CA, (2000).
3. Sahotra Sarkar (editor), *The Philosophy and History of Molecular Bi- ology*, Kluwer Academic Publishers, Boston, (1996).
4. James D. Watson et al. *Molecular Biology of the Gene, 4th Edition*, Benjamin-Cummings, (1988).
5. J.S. Fruton, *Proteins, Enzymes, and Genes*, Yale University Press, New Haven, (1999).

6. S.E. Lauria, *Life, the Unfinished Experiment*, Charles Scribner's Sons, New York (1973).
7. A. Lwoff, *Biological Order*, MIT Press, Cambridge MA, (1962).
8. James D. Watson, *The Double Helix*, Athenium, New York (1968).
9. F. Crick, *The genetic code*, Scientific American, *202*, 66-74 (1962).
10. F. Crick, *Central dogma of molecular biology*, Nature, *227*, 561-563 (1970).
11. David Freifelder (editor), *Recombinant DNA, Readings from the Scientific American*, W.H. Freeman and Co. (1978).
12. James D. Watson, John Tooze and David T. Kurtz, *Recombinant DNA, A Short Course*, W.H. Freeman, New York (1983).
13. Richard Hutton, *Biorevolution, DNA and the Ethics of Man-Made Life*, The New American Library, New York (1968).
14. Martin Ebon, *The Cloning of Man*, The New American Library, New York (1978).
15. Sheldon Krimsky, *Genetic Alchemy: The Social History of the Recombinant DNA Controversy*, MIT Press, Cambridge Mass (1983).
16. M. Lappe, *Germs That Won't Die*, Anchor/Doubleday, Garden City N.Y. (1982).
17. M. Lappe,*Broken Code*, Sierra Club Books, San Francisco (1984).
18. President's Commission for the Study of Ethical Problems in Medicine and Biomedical and Behavioral Research, *Splicing Life: The Social and Ethical Issues of Genetic Engineering with Human Beings*, U.S. Government Printing Office, Washington D.C. (1982).
19. U.S. Congress, Office of Technology Assessment, *Impacts of Applied Genetics - Microorganisms, Plants and Animals*, U.S. Government Printing Office, Washington D.C. (1981).
20. W.T. Reich (editor), *Encyclopedia of Bioethics*, The Free Press, New York (1978).
21. Martin Brown (editor), *The Social Responsibility of the Scientist*, The Free Press, New York (1970).
22. B. Zimmerman, *Biofuture*, Plenum Press, New York (1984).
23. John Lear, *Recombinant DNA, The Untold Story*, Crown, New York (1978).
24. B. Alberts, D. Bray, J. Lewis, M. Raff, K. Roberts and J.D. Watson, *Molecular Biology of the Cell*, Garland, New York (1983).
25. C. Woese, *The Genetic Code; The Molecular Basis for Genetic Expression*, Harper and Row, New York, (1967).
26. F.H.C. Crick, *The Origin of the Genetic Code*, J. Mol. Biol. *38*, 367-379 (1968).
27. M.W. Niernberg, *The genetic code: II*, Scientific American, *208*, 80-94 (1962).
28. L.E. Orgel, *Evolution of the Genetic Apparatus*, J. Mol. Biol. *38*, 381-393 (1968).
29. Melvin Calvin, *Chemical Evolution Towards the Origin of Life, on Earth and Elsewhere*, Oxford University Press (1969).
30. R. Shapiro, *Origins: A Skeptic's Guide to the Origin of Life*, Summit Books, New York, (1986).
31. J. William Schopf, *Earth's earliest biosphere: its origin and evolution*, Princeton University Press, Princeton, N.J., (1983).

32. J. William Schopf (editor), *Major Events in the History of Life*, Jones and Bartlet, Boston, (1992).
33. Robert Rosen, *Life itself: a comprehensive inquiry into the nature, origin and fabrication of life*, Colombia University Press, (1991).
34. R.F. Gesteland, T.R Cech, and J.F. Atkins (editors), *The RNA World, 2nd Edition*, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York, (1999).
35. C. de Duve, Blueprint of a Cell, Niel Patterson Publishers, Burlington N.C., (1991).
36. C. de Duve, *Vital Dust; Life as a Cosmic Imperative*, Basic Books, New York, (1995).
37. F. Dyson, *Origins of Life*, Cambridge University Press, (1985).
38. S.A. Kaufman, *Antichaos and adaption*, Scientific American, 265, 78-84, (1991).
39. S.A. Kauffman, *The Origins of Order*, Oxford University Press, (1993).
40. F.J. Varela and J.-P. Dupuy, *Understanding Origins: Contemporary Views on the Origin of Life, Mind and Society*, Kluwer, Dordrecht, (1992).
41. Stefan Bengtson (editor) *Early Life on Earth; Nobel Symposium No. 84*, Colombia University Press, New York, (1994).
42. Herrick Baltscheffsky, *Origin and Evolution of Biological Energy Con- version*, VCH Publishers, New York, (1996).
43. J. Chilea-Flores, T. Owen and F. Raulin (editors), *First Steps in the Origin of Life in the Universe*, Kluwer, Dordrecht, (2001).
44. R.E. Dickerson, Nature *283*, 210-212 (1980).
45. R.E. Dickerson, Scientific American *242*, 136-153 (1980).
46. C.R. Woese, *Archaebacteria*, Scientific American *244*, 98-122 (1981).
47. N. Iwabe, K. Kuma, M. Hasegawa, S. Osawa and T. Miyata, *Evolutionary relationships of archaebacteria, eubacteria, and eukaryotes inferred phylogenetic trees of duplicated genes*, Proc. Nat. Acad. Sci. USA *86*, 9355-9359 (1989).
48. C.R. Woese, O. Kundler, and M.L. Wheelis, *Towards a Natural System of Organisms: Proposal for the Domains Archaea, Bacteria and Eucaria*, Proc. Nat. Acad. Sci. USA *87*, 4576-4579 (1990).
49. W. Ford Doolittle, Phylogenetic Classification and the Universal Tree, Science, *284*, (1999).
50. G. Wächterhäuser, *Pyrite formation, the first energy source for life: A hypothesis*, Systematic and Applied Microbiology *10*, 207-210 (1988).
51. G. Wächterhäuser, *Before enzymes and templates: Theory of surface metabolism*, Microbiological Reviews, *52*, 452-484 (1988).
52. G. Wächterhäuser, Evolution of the first metabolic cycles, Proc. Nat. Acad. Sci. USA *87*, 200-204 (1990).
53. G. Wächterhäuser, *Groundworks for an evolutionary biochemistry the iron-sulfur world*, Progress in Biophysics and Molecular Biology **58**, 85-210 (1992).
54. M.J. Russell and A.J. Hall, *The emergence of life from iron monosulphide bubbles at a submarine hydrothermal redox and pH front* J. Geol. Soc. Lond. *154*, 377-402, (1997).
55. L.H. Caporale (editor), *Molecular Strategies in Biological Evolution*, Ann. N.Y. Acad. Sci., May 18, (1999).

56. W. Martin and M.J. Russell, *On the origins of cells: a hypothesis for the evolutionary transitions from abiotic geochemistry to chemoautotrophic prokaryotes, and from prokaryotes to nucleated cells*, Philos. Trans. R. Soc. Lond. B Biol. Sci., *358*, 59-85, (2003).
57. Werner Arber, *Elements in Microbal Evolution*, J. Mol. Evol. *33, 4* (1991).
58. Michael Gray, *The Bacterial Ancestry of Plastids and Mitochondria*, BioScience, *33*, 693-699 (1983).
59. Michael Grey, *The Endosymbiont Hypothesis Revisited*, International Review of Cytology, *141*, 233-257 (1992).
60. Lynn Margulis and Dorian Sagan, *Microcosmos: Four Billion Years of Evolution from Our Microbal Ancestors*, Allan and Unwin, London, (1987).
61. Lynn Margulis and Rene Fester, eds., *Symbiosis as as Source of Evolutionary Innovation: Speciation and Morphogenesis*, MIT Press, (1991).
62. Charles Mann, *Lynn Margulis: Science's Unruly Earth Mother*, Science, *252*, 19 April, (1991).
63. Jan Sapp, *Evolution by Association; A History of Symbiosis*, Oxford University Press, (1994).
64. J.A. Shapiro, *Natural genetic engineering in evolution*, Genetics, *86*, 99-111 (1992).
65. E.M. De Robertis et al., *Homeobox genes and the vertebrate body plan*, Scientific American, July, (1990).
66. J.S. Schrum, T.F. Zhu and J.W. Szostak, *The origins of cellular life*, Cold Spring Harb. Perspect. Biol., May 19 (2010).
67. I. Budin and J.W. Szostak, *Expanding Roles for Diverse Physical Phenomena During the Origin of Life*, Annu. Rev. Biophys., *39*, 245-263, (2010).
68. P.J. Bowler, *Evolution: The History of an Idea*, University of California Press, (1989).
69. D.J. Putuyma, *Evolutionary Biology*, Sinauer Associates, Sunderland Mass., (1986).
70. B. Glass, 0. Temkin, and W.L. Strauss, eds., *Forerunners of Darwin: 1745-1859*, Johns Hopkins Press, Baltimore, (1959).
71. R. Milner, *The Encyclopedia of Evolution*, an Owl Book, Henry Holt and Company, New York, (1990).
72. T.A. Appel, *The Cuvier-Geoffroy Debate: French Biology in the Decades before Darwin*, Oxford University Press, (1987).
73. P.J. Bowler, *Fossils and Progress: Paleontology and the Idea of Progressive Evolution in the Nineteenth Century*, Science History Publications, New York, (1976).
74. H. Torrens, *Presidential Address: Mary Anning (1799-1847) of Lyme; 'the greatest fossilist the world ever knew'*, British Journal of the History of Science, *28*, 257-284, (1995).
75. P. Corsi, *The Age of Lamarck: Evolutionary Theories in France, 1790-1834*, University of California Press, Berkeley, (1988).
76. C.C. Gillispie, *Genesis and Geology: A Study in the Relations of Scientific Thought, Natural Theology and Social Opinion in Great Britain, 1790-1850*, Harvard University Press, Cambridge Mass., (1951).

77. M. McNeil, *Under the Banner of Science: Erasmus Darwin and his Age*, Manchester University Press, Manchester, (1987).
78. L.G. Wilson, *Sir Charles Lyell's Scientific Journals on the Species Question*, Yale University Press, New Haven, (1970).
79. M.J.S. Rudwick, *The Meaning of Fossils: Episodes in the History of Paleontology, 2nd ed.*, University of Chicago Press, (1985).
80. A.B. Adams, *Eternal Quest: The Story of the Great Naturalists*, G.P. Putnam's Sons, New York, (1969).
81. A.S. Packard, *Lamarck, the Founder of Evolution: His Life and Work*, Longmans, Green, and Co., New York, (1901).
82. C. Darwin, *An historical sketch of the progress of opinion on the Origin of Species, previously to the publication of this work*, Appended to third and later editions of *On the Origin of Species*, (1861).
83. L. Eiseley, *Darwin's Century: Evolution and the Men who Discovered It*, Doubleday, New York, (1958).
84. H.F. Osborne, *From the Greeks to Darwin: The Development of the Evolution Idea Through Twenty-Four Centuries*, Charles Scribner and Sons, New York, (1929).
85. Sir Julian Huxley and H.B.D. Kettlewell, *Charles Darwin and his World*, Thames and Hudson, London, (1965).
86. Allan Moorehead, *Darwin and the Beagle*, Penguin Books Ltd., (1971).
87. Francis Darwin (editor), *The Autobiography of Charles Darwin and Selected Letters*, Dover, New York, (1958).
88. Charles Darwin, *The Voyage of the Beagle*, J.M. Dent and Sons Ltd., London, (1975).
89. Charles Darwin, *The Origin of Species*, Collier MacMillan, London, (1974).
90. Charles Darwin, *The Expression of Emotions in Man and Animals*, The University of Chicago Press (1965).
91. D.W. Forest, *Francis Galton, The Life and Work of a Victorian Genius*, Paul Elek, London (1974).
92. Ruth Moore, *Evolution*, Time-Life Books (1962).
93. L. Barber, *The Heyday of Natural History: 1820-1870*, Doubleday and Co., Garden City, New York, (1980).
94. A. Desmond, *Huxley*, Addison Wesley, Reading, Mass., (1994).
95. R. Owen, (P.R. Sloan editor), *The Hunterian Lectures in Comparative Anatomy*, May-June, 1837, University of Chicago Press, (1992).
96. C. Nichols, *Darwinism and the social sciences*, Phil. Soc. Scient. *4*, 255-277 (1974).
97. M. Ruse, *The Darwinian Revolution*, University of Chicago Press, (1979).
98. A. Desmond and J. Moore, *Darwin*, Penguin Books, (1992).
99. R. Dawkins, *The Extended Phenotype*, Oxford University Press, (1982).
100. R. Dawkins, *The Blind Watchmaker*, W.W. Norton, (1987).
101. R. Dawkins, *River out of Eden: A Darwinian View of Life*, Harper Collins, (1995).
102. R. Dawkins, *Climbing Mount Improbable*, W.W. Norton, (1996).
103. S.J. Gould, *Ever Since Darwin*, W.W. Norton, (1977).
104. S.J. Gould, *The Panda's Thumb*, W.W. Norton, (1980).

105. S.J. Gould, *Hen's Teeth and Horse's Toes*, W.W. Norton, (1983).
106. S.J. Gould, *The Burgess Shale and the Nature of History*, W.W. Norton, (1989).
107. R.G.B. Reid, *Evolutionary Theory: The Unfinished Synthesis*, Croom Helm, (1985).
108. M. Ho and P.T. Saunders, editors, *Beyond Neo-Darwinism: An Introduction to a New Evolutionary Paradigm*, Academic Press, London, (1984).
109. J.Maynard Smith, *Did Darwin Get it Right? Essays on Games, Sex and Evolution*, Chapman and Hall, (1989).
110. E. Sober, *The Nature of Selection: Evolutionary Theory in Philosophical Focus*, University of Chicago Press, (1984).
111. B.K. Hall, *Evolutionary Developmental Biology*, Chapman and Hall, London, (1992).
112. J. Thompson, *Interaction and Coevolution*, Wiley and Sons, (1982).
113. N. Tinbergen, *The Study of Instinct*, Oxford University Press, (1951).
114. N. Tinbergen, *Social Behavior in Animals*, Methuen, London, (1953).
115. N. Tinbergen, *The Animal in its World: Explorations of an Ethologist*, Allan and Unwin, London, (1973).
116. K. Lorenz, *On the evolution of behavior*, Scientific American, December, (1958).
117. K. Lorenz, *Studies in Animal and Human Behavior. I and II.*, Harvard University Press, (1970) and (1971).
118. P.H. Klopfer and J.P. Hailman, *An Introduction to Animal Behavior: Ethology's First Century*, Prentice-Hall, New Jersey, (1969).
119. J. Jaynes, *The historical origins of "Ethology" and "Comparative Psychology"*, Anim. Berhav. *17*, 601-606 (1969).
120. W.H. Thorpe, *The Origin and Rise of Ethology: The Science of the Natural Behavior of Animals*, Heinemann, London, (1979).
121. R.A. Hinde, *Animal Behavior: A Synthesis of Ethological and Comparative Psychology*, McGraw-Hill, New York, (1970).
122. J.H. Crook, editor, *Social Behavior in Birds and Mammals*, Academic Press, London, (1970).
123. P. Ekman, editor, *Darwin and Facial Expression*, Academic Press, New York, (1973).
124. P. Ekman, W.V. Friesen and P. Ekworth, *Emotions in the Human Face*, Pergamon, New York, (1972).
125. N. Burton Jones, editor, *Ethological Studies of Child Behavior*, Cam- bridge University Press, (1975).
126. M. von Cranach, editor, *Methods of Inference from Animals to Human Behavior*, Chicago/Mouton, Haag, (1976); Aldine, Paris, (1976).
127. K. Lorenz, *On Aggression*, Bantam Books, (1977).
128. I. Eibl-Eibesfeld, *Ethology, The Biology of Behavior*, Holt, Rinehart and Winston, New York, (1975).
129. P.P.G. Bateson and R.A. Hinde, editors, *Growing Points in Ethology*, Cambridge University Press, (1976).
130. J. Bowlby, *By ethology out of psychoanalysis: An experiment in interbreeding, Animal Behavior*, *28* , 649-656 (1980).
131. B.B. Beck, *Animal Tool Behavior*, Garland STPM Press, New York, (1980).

132. R. Axelrod, *The Evolution of Cooperation*, Basic Books, New York, (1984).
133. J.D. Carthy and F.L. Ebling, *The Natural History of Aggression*, Academic Press, New York, (1964)
134. D.L. Cheney and R.M. Seyfarth, *How Monkeys See the World: Inside the Mind of Another Species*, University of Chicago Press, (1990).
135. F. De Waal, *Chimpanzee Politics*, Cape, London, (1982).
136. M. Edmunds, *Defense in Animals*, Longman, London, (1974).
137. R.D. Estes, *The Behavior Guide to African Mammals*, University of California Press, Los Angeles, (1991).
138. R.F. Ewer, *Ethology of Mammals*, Logos Press, London, (1968).
139. H. Lodish, A. Berk, S.L. Zipursky, P. Matsudaira, D. Baltimore, and J. Darnell, *Molecular Cell Biology, 4th Edition*, W.H. Freeman, New York, (2000).
140. Lily Kay, *Who Wrote the Book of Life? A History of the Genetic Code*, Stanford University Press, Stanford CA, (2000).
141. Sahotra Sarkar (editor), *The Philosophy and History of Molecular Bi- ology*, Kluwer Academic Publishers, Boston, (1996).
142. James D. Watson et al. *Molecular Biology of the Gene, 4th Edition*, Benjamin-Cummings, (1988).
143. J.S. Fruton, *Proteins, Enzymes, and Genes*, Yale University Press, New Haven, (1999).
144. S.E. Lauria, *Life, the Unfinished Experiment*, Charles Scribner's Sons, New York (1973).
145. A. Lwoff, *Biological Order*, MIT Press, Cambridge MA, (1962).
146. James D. Watson, *The Double Helix*, Athenium, New York (1968).
147. F. Crick, *The genetic code*, Scientific American, *202*, 66-74 (1962).
148. F. Crick, *Central dogma of molecular biology*, Nature, *227*, 561-563 (1970).
149. David Freifelder (editor), *Recombinant DNA, Readings from the Scientific American*, W.H. Freeman and Co. (1978).
150. James D. Watson, John Tooze and David T. Kurtz, *Recombinant DNA, A Short Course*, W.H. Freeman, New York (1983).
151. Richard Hutton, *Biorevolution, DNA and the Ethics of Man-Made Life*, The New American Library, New York (1968).
152. Martin Ebon, *The Cloning of Man*, The New American Library, New York (1978).
153. Sheldon Krimsky, *Genetic Alchemy: The Social History of the Recombinant DNA Controversy*, MIT Press, Cambridge Mass (1983).
154. M. Lappe, *Germs That Won't Die*, Anchor/Doubleday, Garden City N.Y. (1982).
155. M. Lappe,**Broken Code**, Sierra Club Books, San Francisco (1984).
156. President's Commission for the Study of Ethical Problems in Medicine and Biomedical and Behavioral Research, *Splicing Life: The Social and Ethical Issues of Genetic Engineering with Human Beings*, U.S. Government Printing Office, Washington D.C. (1982).

157. U.S. Congress, Office of Technology Assessment, *Impacts of Applied Genetics - Microorganisms, Plants and Animals*, U.S. Government Printing Office, Washington D.C. (1981).
158. W.T. Reich (editor), *Encyclopedia of Bioethics*, The Free Press, New York (1978).
159. Martin Brown (editor), *The Social Responsibility of the Scientist*, The Free Press, New York (1970).
160. B. Zimmerman, *Biofuture*, Plenum Press, New York (1984).
161. John Lear, *Recombinant DNA, The Untold Story*, Crown, New York (1978).
162. B. Alberts, D. Bray, J. Lewis, M. Raff, K. Roberts and J.D. Watson, **Molecular Biology of the Cell**, Garland, New York (1983).
163. C. Woese, *The Genetic Code; The Molecular Basis for Genetic Expression*, Harper and Row, New York, (1967).
164. F.H.C. Crick, *The Origin of the Genetic Code*, J. Mol. Biol. *38*, 367-379 (1968).
165. M.W. Niernberg, *The genetic code: II*, Scientific American, *208*, 80-94 (1962).
166. L.E. Orgel, *Evolution of the Genetic Apparatus*, J. Mol. Biol. *38*, 381-393 (1968).
167. Melvin Calvin, *Chemical Evolution Towards the Origin of Life, on Earth and Elsewhere*, Oxford University Press (1969).
168. R. Shapiro, *Origins: A Skeptic's Guide to the Origin of Life*, Summit Books, New York, (1986).
169. J. William Schopf, *Earth's earliest biosphere: its origin and evolution*, Princeton University Press, Princeton, N.J., (1983).
170. J. William Schopf (editor), *Major Events in the History of Life*, Jones and Bartlet, Boston, (1992).
171. Robert Rosen, *Life itself: a comprehensive inquiry into the nature, origin and fabrication of life*, Colombia University Press, (1991).
172. R.F. Gesteland, T.R Cech, and J.F. Atkins (editors), *The RNA World, 2nd Edition*, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York, (1999).
173. C. de Duve, *Blueprint of a Cell*, Niel Patterson Publishers, Burlington N.C., (1991).
174. C. de Duve, *Vital Dust; Life as a Cosmic Imperative*, Basic Books, New York, (1995).
175. F. Dyson, *Origins of Life*, Cambridge University Press, (1985).
176. S.A. Kaufman, *Antichaos and adaption*, Scientific American, *265*, 78-84, (1991).
177. S.A. Kauffman, *The Origins of Order*, Oxford University Press, (1993).
178. F.J. Varela and J.-P. Dupuy, *Understanding Origins: Contemporary Views on the Origin of Life, Mind and Society*, Kluwer, Dordrecht, (1992).
179. Stefan Bengtson (editor) *Early Life on Earth; Nobel Symposium No. 84*, Colombia University Press, New York, (1994).
180. Herrick Baltscheffsky, *Origin and Evolution of Biological Energy Con- version*, VCH Publishers, New York, (1996).
181. J. Chilea-Flores, T. Owen and F. Raulin (editors), *First Steps in the Origin of Life in the Universe*, Kluwer, Dordrecht, (2001).
182. R.E. Dickerson, Nature *283*, 210-212 (1980).
183. R.E. Dickerson, Scientific American *242*, 136-153 (1980).
184. C.R. Woese, *Archaebacteria*, Scientific American *244*, 98-122 (1981).

185. N. Iwabe, K. Kuma, M. Hasegawa, S. Osawa and T. Miyata, *Evolutionary relationships of archaebacteria, eubacteria, and eukaryotes inferred phylogenetic trees of duplicated genes*, Proc. Nat. Acad. Sci. USA *86*, 9355-9359 (1989).
186. C.R. Woese, O. Kundler, and M.L. Wheelis, *Towards a Natural System of Organisms: Proposal for the Domains Archaea, Bacteria and Eucaria*, Proc. Nat. Acad. Sci. USA *87*, 4576-4579 (1990).
187. W. Ford Doolittle, *Phylogenetic Classification and the Universal Tree*, Science, *284*, (1999).
188. G. Wächterhäuser, *Pyrite formation, the first energy source for life: A hypothesis*, Systematic and Applied Microbiology *10*, 207-210 (1988).
189. G. Wächterhäuser, *Before enzymes and templates: Theory of surface metabolism*, Microbiological Reviews, *52*, 452-484 (1988).
190. G. Wächterhäuser, *Evolution of the first metabolic cycles*, Proc. Nat. Acad. Sci. USA *87*, 200-204 (1990).
191. G. Wächterhäuser, *Groundworks for an evolutionary biochemistry the iron-sulfur world*, Progress in Biophysics and Molecular Biology **58**, 85-210 (1992).
192. M.J. Russell and A.J. Hall, *The emergence of life from iron monosulphide bubbles at a submarine hydrothermal redox and pH front* J. Geol. Soc. Lond. *154*, 377-402, (1997).
193. L.H. Caporale (editor), *Molecular Strategies in Biological Evolution*, Ann. N.Y. Acad. Sci., *May 18*, (1999).
194. W. Martin and M.J. Russell, *On the origins of cells: a hypothesis for the evolutionary transitions from abiotic geochemistry to chemoautotrophic prokaryotes, and from prokaryotes to nucleated cells*, Philos. Trans. R. Soc. Lond. B Biol. Sci., *358*, 59-85, (2003).
195. Werner Arber, *Elements in Microbal Evolution*, J. Mol. Evol. *33, 4* (1991).
196. Michael Gray, *The Bacterial Ancestry of Plastids and Mitochondria*, BioScience, *33*, 693-699 (1983).
197. Michael Grey, *The Endosymbiont Hypothesis Revisited*, International Review of Cytology, *141*, 233-257 (1992).
198. Lynn Margulis and Dorian Sagan, *Microcosmos: Four Billion Years of Evolution from Our Microbal Ancestors*, Allan and Unwin, London, (1987).
199. Lynn Margulis and Rene Fester, eds., *Symbiosis as as Source of Evolutionary Innovation: Speciation and Morphogenesis*, MIT Press, (1991).
200. Charles Mann, *Lynn Margulis: Science's Unruly Earth Mother*, Science, *252*, 19 April, (1991).
201. Jan Sapp, *Evolution by Association; A History of Symbiosis*, Oxford University Press, (1994).
202. J.A. Shapiro, *Natural genetic engineering in evolution*, Genetics, *86*, 99-111 (1992).
203. E.M. De Robertis et al., *Homeobox genes and the vertebrate body plan*, Scientific American, *July*, (1990).
204. J.S. Schrum, T.F. Zhu and J.W. Szostak, *The origins of cellular life*, Cold Spring Harb. Perspect. Biol., *May 19* (2010).

205. I. Budin and J.W. Szostak, *Expanding Roles for Diverse Physical Phenomena During the Origin of Life*, Annu. Rev. Biophys., *39*, 245-263, (2010).
206. M. Eigen et al., *The Origin of genetic information*, Scientific American, April, 78-94 (1981).
207. L.E. Kay, *Cybernetics, information, life: The emergence of scriptural representations of heredity*, Configurations, *5*, 23-91 (1997).
208. T.D. Schneider, G.D. Stormo, L. Gold and A. Ehrenfeucht, *Information content of binding sites on nucleotide sequences*, J. Mol. Biol. **88**, 415-431 (1986).
209. J. Avery, *A model for biological specificity*, Int. J. Quant. Chem., *26*, 843 (1984).
210. P.G. Mezey, *Shape in Chemistry: An Introduction to Molecular Shape and Topology*, VCH Publishers, New York, (1993).
211. P.G. Mezey, *Potential Energy Hypersurfaces*, Elsevier, Amsterdam, (1987).
212. P.G. Mezey, *Molecular Informatics and Topology in Chemistry, in Topology in Chemistry*, R.B. King and D.H. Rouvray, eds., Ellis Horwood, Pbl., U.K., (2002).
213. G. Stent, *Cellular communication*, Scientific American, *227*, 43-51 (1972).
214. A. Macieira-Coelho, editor, *Signaling Through the Cell Matrix*, Progress in Molecular and Subcellular Biology, *25*, Springer, (2000).
215. D.H. Hubel, *The visual cortex of the brain*, Scientific American, *209, 54, November*, (1963).
216. J.Z. Young, *Programs of the Brain*, Oxford University Press, (1978).
217. J.Z. Young, *Philosophy and the Brain*, Oxford University Press, (1987).
218. K. von Frisch, *Dialects in the languages of bees*, Scientific American, **August**, (1962).
219. R.A. Hinde, *Non-Verbal Communication*, Cambridge University Press, (1972).
220. E.O. Wilson, *Animal communication*, Scientific American, *227*, 52-60 (1972).
221. E.O. Wilson, *Sociobiology*, Harvard University Press, (1975).
222. H.S. Terrace, L.A. Petitto, et al., *Can an ape create a sentence?*, Science, *206*, 891-902 (1979).
223. S. Savage-Rumbaugh, R. Lewin, et al., Kanzi: *The Ape at the Brink of the Human Mind*, John Wiley and Sons, New York, (1996).
224. R.W. Rutledge, B.L. Basore, and R.J. Mulholland, *Ecological stability: An information theory viewpoint*, J. Theor. Biol., *57*, 355-371 (1976).
225. L. Johnson, *Thermodynamics and ecosystems*, in *The Handbook of Environmental Chemistry*, O. Hutzinger, editor, Springer Verlag, Heidelberg, (1990), pp. 2-46.
226. C. Pahl-Wostl, *Information theoretical analysis of functional temporal and spatial organization in flow networks*, Math. Comp. Model. *16 (3)*, 35-52 (1992).
227. C. Pahl-Wostl, *The Dynamic Nature of Ecosystems: Chaos and Order Intertwined*, Wiley, New York, (1995).
228. E.D. Schneider and J.J. Kay, *Complexity and thermodynamics: Towards a new ecology*, Futures, *24 (6)*, 626-647 (1994).
229. R.E. Ulanowicz,**Ecology, the Ascendent Perspective**, Colombia University Press, New York, (1997).
230. H. Lodish, A. Berk, S.L. Zipursky, P. Matsudaira, D. Baltimore, and J. Darnell, *Molecular Cell Biology, 4th Edition*, W.H. Freeman, New York, (2000).

Index