Chapter 1
Life on Earth

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Life on Earth was initiated some 10 billion years after the Universe was created. Life was created on the basis of, and has to obey, the laws of physics. At the same time, physical laws are useless for understanding living processes because the combination of atoms into molecules and molecules into cells and organisms is based on emergent properties that only arise through the interactions between the components, the cells, the organisms, the ecosystems, and the whole biosphere of the little blue-green planet we live on.

Our powerful modern biotechnologies undoubtedly do have the potential to change life on Earth. The fundamental question arising is then: Do we really know what we are changing, and the risks that are involved?

This chapter is intended to give a brief overview of the evolution and constituents of life. Hence, it presents basic concepts related to the issues treated more comprehensively in the more specialized parts of this book. The chapter is organized according to the following outline:

1. Origins of Life

1.1 Tellus, our common spaceship
The Milky Way is a medium-sized galaxy. The Sun, located in one of its spiral arms, is a medium-sized star formed by atoms released from a nearby supernova. The Sun evolved approximately 4.5 billion years ago. It has enough hydrogen fuel to burn for another 5 billion years.

During the birth process of the Sun, some of the surrounding material assembled into small aggregates that grew and collided and merged with one another to eventually stabilize as its orbiting planets, moons and comets. Importantly, some of these orbiting aggregates contained iron and radioactive elements that are now the Earth's broiling core, the silicon that forms its crust. Yet most important was the presence of carbon, oxygen, nitrogen, and other elements that are essential for life.

Comets colliding with the developing Earth contributed even more atoms from distant supernovae, and also brought in a great deal of water in the form of ice. Gases from the Earth's interior were released through fissures and volcanoes, and were trapped by gravity to form the early atmosphere. The floating surface settled into large masses that drift and crash into each other, creating continuous geological activity that defines and changes the continents and ocean basins. It took half a billion years before the physical conditions on Earth became such that life could originate and continue.

1.2 The chemical prerequisites
Life depends on atoms that form bonds with one another and hence associate into molecules, and also on smaller molecules to associate into larger molecules. Such events are defined within chemistry, which again may be reduced to physics. Chemical binding and association of molecules can only take place under certain conditions. For chemical reactions to proceed there are three main compulsory conditions. First, an available flow of energy, from source to sink must be available. The Earth has two important energy sources: The Sun and the planet's own molten core. Second, temperatures must be such that atoms and molecules can coexist in solid, liquid and gaseous forms. Third, the atoms that are more likely to engage in early biochemical reactions – carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulphur – must be present. These are called 'the Big Six' of living systems. They can form bonds with one another under conditions of energy flow, e.g. hydrogen combines with oxygen to form water, carbon combines with oxygen to form carbon dioxide, carbon starts to combine with all the others and forms more complex molecules.

1.3. The early biochemicals and building blocks
In order for life to start, the so-called building blocks of life – water, carbon dioxide and small molecules such as formaldehyde, methane and hydrogen sulphide – had to be generated, and consecutively these had to associate into larger assemblies, the early biochemicals. Small but complex building blocks may have accumulated in the waters of the Earth from the time of its birth, approximately 4.5 billion years ago. This so-called 'primal soup', contained three groups of small molecules called sugars, amino acids and nucleotides. The latter comprised two kinds, ribonucleotides and deoxyribonucleotides. These are the starting materials for all forms of life on Earth. Approximately 4 billion years ago the formation of biomolecules from the primal soup building blocks was initiated. Recently, it has become common to speak of the first stages of life as having developed in a 'RNA world'. There are good reasons to believe that relatively simple cells with self-replicating RNA were the first to inhabit the earth. The first cells may simply have

been a lipid membrane-enclosed self-replicating RNA that had taken on the ability to direct synthesis of ribonucleotides and membrane lipids. This might make self-replication possible.

2. Cells

The cells of the 'RNA world' evolved into cells whose genes are encoded in DNA molecules, and later they vanished. Hence, we are now living in a DNA world. DNA uses deoxyribonucleotides instead of ribonucleotides as precursors, and is more stable than RNA. The basic concept is, however, the same: a long chain of deoxyribonucleotides carries genes that code for molecular products making replication of the chain possible.

The genes encoded in DNA came to specify large molecules called *proteins*. Some proteins are responsible for ensuring that the biochemical processes inside the cell proceed accurately and efficiently. These proteins are called *enzymes*.

Life depends on the ability of cells to construct new copies of itself, remember how to do it and pass the instructions on to the daughter cells. The key role of DNA is to encode readable instructions for how to make proteins and pass these instructions along during replication. Along the way cells acquired the ability to extract energy from small molecules such as hydrogen and hydrogen sulphide. At some point, they also invented the capacity to carry out photosynthesis, i.e. to capture energy from sunlight and transfer it into chemical bonds. Most of the living creatures are single celled, but some, e.g. humans and plants, are made up of many different kinds of cells that cooperate to form a single organism. Each cell has a membrane around it; a thin film of lipid keeping the outside out and the inside in, and each cell contains the DNA instructions for its various activities.

2.1. Proteins

The activities in the cells are executed by proteins, and protein functions are all about *shape*. Proteins have protuberances and pockets and long, straight as well as tightly coiled parts. Each part is called a *domain*. Domains are the interactive sites of proteins.

When it is made, a protein starts out as a long chain of amino acids. There are twenty different kinds of amino acids. Each of them has its own properties. Some are greasy, some are bulky, while others are long and slender. Some have negative charges, others positive charges. The DNA sequence in a given gene dictates the sequence of amino acids in a given protein chain. Once a protein chain is made, it folds up. Amino acids that prefer to be next to each other, such as a group of greasy ones, may associate to form one domain. Amino acids with negative charges might line up next to some with positive charges to form a second domain. A bulky amino acid might cause a protuberant domain to stick farther out. The result is a protein with a distinctive overall size and shape that displays a collection of very specific domains. A second chain with a different sequence of amino acids will self-assemble into a protein with a different size, shape and set of domains. Protuberances and pockets are important for proteins to form, as in a jigsaw puzzle, *multi-protein complexes* that perform many important functions in the cell. Furthermore, pockets are crucial to the functions of proteins that are called *enzymes*.

2.1.1 Enzymes

The pockets made by the folding of an enzyme are not destined to interact, e.g. make complexes, with other proteins. Instead, they are shaped to cater for interactions with small molecules that the cell must handle chemically. The enzyme will have one pocket exactly shaped for each of the two sugar molecules, e.g. glucose and galactose. When both pockets are filled the enzyme changes its shape and brings the sugars close enough together for a chemical bond to be established between

them. The combined glucose-galactose molecule then pops out, the enzyme resumes its original shape, and the process may start all over again. The enzyme is said to *catalyze* the chemical reaction. If many sugar molecules are joined together in this way the end result is a *polysaccharide*. Such sugar polymers are important in many cellular functions.

Every cell is packed with thousands of different kinds of enzymes. Each enzyme displays a distinctive surface combination of protuberants and pockets, and is able to catalyze one or several chemical reactions. Some enzymes catalyze the formation of chemical bonds, as in the sugar-sugar example. Others catalyze the disruption of chemical bonds to generate smaller molecules from bigger ones. Some enzymes catalyze long chains of amino acids (proteins), nucleotides (DNA or RNA) or glycerides (lipids). All these polymers are key cellular components.

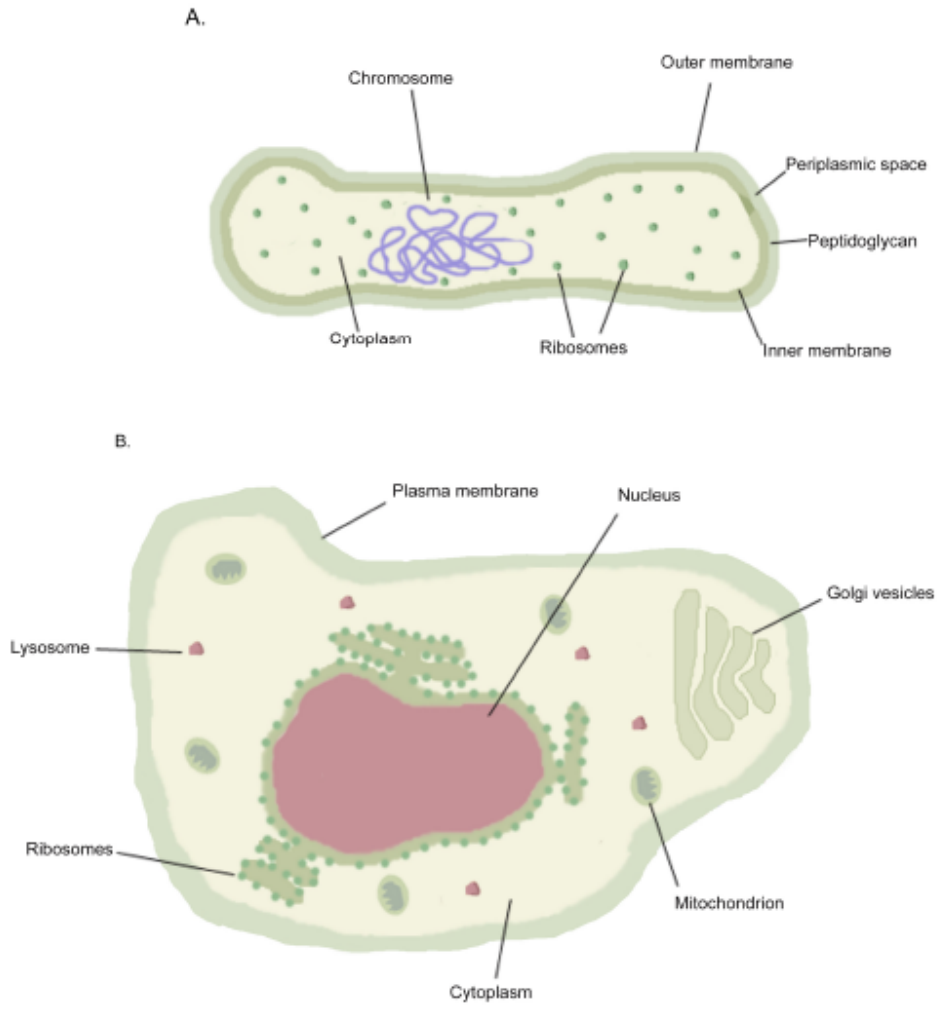

Figure 1.1. Outline of a generic prokaryotic (a) cell and eukaryotic (b) cell.

2.2. Channels and pumps
Such protein complexes space the cell membrane and determine which electrically charged ions, e.g. calcium, potassium and chloride, are allowed to cross the membrane and at what rate. Some of these ions are positively charged while others are negatively charged. Their net distribution generates ion gradients. For example, the inside of the cell is rendered more negative than the outside, and contains more potassium and less sodium and calcium than the outside. If such electrochemical gradients do not function properly cells will quickly disrupt and die.

2.3. Cascades and receptors
Life proceeds as *cascades of shape changes*. Three proteins may fit together into a complex that associates with some lipids in the cell membrane to form a sodium channel. When the channel changes its shape, an influx of sodium changes the shape of an internal enzyme so that pockets hidden in its interior become exposed. The pockets are then engaged in chemical reactions that induce another protein to change its shape, and so on. A sequence of such events is called a *cascade*.

Cascades are important for how a cell perceives the world, and for how organisms adjust to changing environmental conditions. All cell membranes carry *receptors* composed of three domains. One domain faces outwards, towards the environment, the second bridges the membrane, and a third faces the cell interior. The outer face carries a pocket exactly shaped to fit some molecule that may be present in the world outside. Such molecules may be hormones, growth factors, odorants, or other signal substances. When a cognate molecule (ligand) has filled its pocket the receptor changes its shape, and the change propagates through the membrane-spanning domain and induces a new conformation in the interior domain. This may, sometimes through intermediary steps, lend enzyme functions to the interior domain. It may now catalyze a shape change in a protein in the interior of the cell, and so on, one shape change catalyzing the next until the 'message' is brought into the cell nucleus to become interpreted. The signal, e.g. the presence of a specific hormone, sets off a *signal transduction cascade* whereby the receptor transduces the external signal into appropriate biochemical reactions.

The inside of the cell is designed to optimize the flowing of cascades. Proteins predetermined to interact with each other have domains, called 'addresses', that target them to the same subcellular location. Each location is optimal for particular biochemical reactions, and is delimitated by a defined boundary, often an intracellular membrane.

2.4. The genes and the genome
Each cell contains a complete set of instructions for how to make all its proteins, and these instructions can be copied so that more cells can be produced. The instructions are stored in DNA, which uses a universal code to specify different amino acid sequences which self-assemble as structural units or three-dimensional enzymes or receptors or channels. Each sector of the DNA that encodes a protein is called a *gene*.

The collection of all genes necessary to specify an organism is called its *genome*. The entire genome must be replicated and transmitted to the next generation for a lineage to continue.

The human genome contains some 25,000 genes. There are approximately 250 different cell types in the human organism, and they all contain exactly the same genome. This immediately informs that the genome is differently expressed in different cells.

There are several hundred thousand proteins expressed in the human organism. This tells us that each gene may give instructions for more than one protein to be made. Different cells express a different assortment of proteins, and the same proteins expressed in different cell types may be present in different relative amounts.

A gene is an instruction for making a protein, and a cell has the option to express that gene and hence contain the protein, or not express that gene and hence lack the protein. It also has the option to express the gene often, and hence have a lot of the protein, or express it rarely and hence have little. These decisions are mediated through domains of DNA that are hooked up to the protein coding sectors, and are called *promoters*.

2.5. Internal clocks: The cell cycle

Cells can switch genes on and off in response to changes in the environment, e.g. through specific signal transduction cascades. In addition, important sets of genes are regulated internally, a good example being the genes that govern what is called the cell cycle.

A cell is made to copy its entire genome and perform DNA replication by an elaborate enzymatic process. Once replication is finished, a second decision is made that allows the cell to divide into two by mitosis. One of the genome copies goes to each of the daughter cells. Then the cell cycle starts over again. The process is bracketed by a large number of sub-decisions, and all are dictated by changing patterns of gene expression, coordinated up- and down-regulated expression of proteins that regulate the different stages of the cell cycle.

The time it takes for a cell cycle to elapse may be influenced by the environment, but cell cycles have an inherent timescale of their own.

3. Multicellular Organisms

The human body contains more than a trillion cells that remain together to form an organism. Each cell possesses the full set of genetic instructions for making a human being, but only some of the instructions are read in a given cell type.

Red blood cells switch on the genes encoding haemoglobin, but never express the genes encoding the hair protein keratin. Hair-follicle cells, on the other hand, switch on keratin, but never haemoglobin genes. Each cell thus recognizes its position and fulfils its specific role.

Each cell type in the body goes through a cell cycle following its own cell-specific rate. Surface cells in the intestines divide twice a day. Liver cells divide only once a year. Some nerve cells do not divide at all. All the diverse cell-specific patterns still generate an organism with a controlled size and shape.

Organisms are characterized by a remarkably complex organization which endows them with the capacity to respond to external stimuli. They have a metabolism that binds or releases energy. They are able to grow, to differentiate and replicate.

Organisms have the remarkable property that they are open systems, maintaining a steady-state balance in spite of much input and output. This *homeostasis* is made possible by elaborate feedback processes, unknown in their precision in any inanimate system. Even the simplest living organisms we know of depend on *c.*550 linked biochemical processes.

Such complexity has often been put forward as the most characteristic feature of living systems. However, complexity is not a fundamental difference between organisms and inorganic systems.

The weather systems on Earth or in any galaxy are also highly complex systems. In general, however, organic systems are more complex by several orders of magnitude than those of inanimate objects.

The complexity of organisms is evident at every hierarchical level, from the nucleus, to the cell, to the organ systems, to the individual, to the species, the ecosystem, and to society.
On each hierarchical level, two clearly recognizable properties are observed: i) units act as wholes, as though they were a single entity, and ii) their characteristics cannot be deduced even from the most complete knowledge of its components. When an organism is assembled from its components, new characteristics of the whole emerge. *Emergent properties* occur also through the inanimate world, but only organisms show such dramatic emergence of new characteristics at every hierarchical level of the system.

3.1. Genotype and phenotype
The presence of the genetic 'programme' gives organisms a peculiar duality, consisting of a *genotype* and a *phenotype*. The genotype is handed over largely unchanged from generation to generation. Occasional mutations, horizontal gene transfer events and recombination introduce some new variability all the time. The genotype interacts with the environment to produce the visible phenotype that we observe.
The genotype dates back to the origin of life. It endows all organisms with their remarkable capability for goal-directed processes, leading to diversification and evolutionary development, a capacity totally absent in the inanimate world.

Since each genome is a unique combination of thousands of different genes, the differences among them cannot be expressed in quantitative terms, but only in qualitative terms. Thus, quality becomes one of the dominant aspects of living organisms and their characteristics. This becomes particularly obvious when comparing properties and activities of different species, e.g. with regard to their courtship displays, pheromones, niche occupation, or whatever else may characterize a particular species.

3.2. Genomic evolution
Evolution can, in a simplistic way, be defined as changes in the frequencies of different sets of instructions for making organisms. Thus, we need to understand how the instructions become different, which happens by mutation. We also need to know how the frequencies of those instructions are changed, and that happens by *natural selection*.

A mutation is a change in the sequence of nucleotides in a genome. A mutation may arise as an uncorrected error during DNA replication. Yet it may also be due to physical or chemical damage if the genome is exposed to environmental agents. Furthermore, both naturally occurring *horizontal gene transfer* and *transgenic engineering* are, by definition, mutations, changing the genome by inserting foreign pieces of DNA into it. Mutations in protein-coding parts of a gene may lead to a change in the amino acid sequence. The new product may have deleterious, beneficial or neutral effects. Mutations in promoters will also have deleterious, beneficial or neutral consequences depending on which nucleotides are altered. Activator or repressor proteins may recognize and bind to a mutated promoter sequence less well, either better or at the same level as the unmodified promoter. Each new gene and promoter is subject to very discriminating and purposeful acts of selection.

3.3. Natural selection

A deleterious gene is likely to be lethal and the new gene will fail to spread, while a beneficial mutation may give the cell or organism an advantage, and hence the new gene may become more prevalent than the previous version.

Mutations change the quality of genes and natural selection changes the frequency of genes. The end results are strongly influenced by context. Evolution is hence contingent on the environmental circumstances in which it is occurring. The traits that define an organism, its motility, its mating behaviour, its perception of odours, its metabolism, or its embryology, are *not* determined by single genes, but by sets of interacting genes and gene products, which again interact with the physical environment and other organisms, in space and time. These complex interactive traits or 'units' are hence the true substrates of evolution.

The general principle is that evolution produces cumulative change. New protein versions do not leap into existence fully formed. Rather, they appear as slightly modified versions of the previous molecules, only a little more efficient, serving an additional function or serving the same function(s) under different conditions. Increasing complexity entails selections of selections of selections.

At the gene level, evolution seems to be remarkably conservative, in spite of all the novelty that emerges. Once a gene sequence encoding a particularly useful protein domain appears, that sequence shows up again and again, in different contexts, in different genes, lineages and species.

As a result, a great deal of homology exists between the genes of all modern organisms. This reflects the fact that all species evolved from the same common ancestor. We have moved through evolution while the same basic sets of protein domains were manipulated.

Most of our genes are akin to most chimpanzee genes, but are also like many of the genes in a fruit fly. The important lesson here is our intimate interrelatedness and close genetic homology with our co-inhabitants of this little blue-green planet. We all came from a singe-celled organism from which the three major branches of life, *bacteria*, the *archea* and the *eukaryotes* developed.

Archea are single-celled organisms that are now confined to hot sulphurous springs and other extreme niches, but their ancestors were probably major parts of life in earlier times when the Earth was very hot and salty. Bacteria are by far the most abundant organisms on the Earth. It has been stated that there are as many bacteria in our gastrointestinal tracts or in a spadeful of soil as there has ever been humans on the planet. Further, the body cells are outnumbered by the bacterial cells the body is hosting.

Eukaryotes are organisms that contain their genome in a separate organelle called the *nucleus*. They also possess an internal cytoskeleton that allows them to move about. More than two billions of years ago, eukaryotic cells engulfed bacteria that became permanent occupants and gave rise to the energy generating organelles called mitochondria and chloroplasts.

Some 600 million years ago, during the Cambrian explosion, numerous eukaryote lineages appeared. Some remained unicellular, while others adopted a multicellular body plan and gave rise to the present day fungi, plants and animals.

Much of the biological evolution entails the development of what organisms are aware of, attracted to or repelled by. Once a sufficient number of species and organisms came into existence, their awareness of each other as prey, predators or symbionts was developed. Further,

when eukaryotic 'sex' was invented, systems were developed to recognize a mate of the correct species, gender, age and quality. In addition, the neuron, a cell type specialized for awareness was invented. This made possible the avenue of awareness called consciousness through more or less elaborated nervous systems.

4. Germline versus Soma

In eukaryotes, the genome is not encoded in a single DNA molecule. The genome is divided into a number of DNA pieces called *chromosomes*. The genome of each species is portioned into a distinctive number of chromosomes. Humans, for instance, have 23 chromosomes, while maize has 10.

Sex entails making two kinds of cells. The *haploid* cell contains one full set of chromosomes while the *diploid* cell has two complete sets. Diploid cells arise when two haploid cells fuse together. Haploid cells are formed when diploid cells give one each of their chromosome sets to two daughter cells.
Formation of a diploid cell occurs during *fertilization*. A haploid sperm or pollen cell from the male fuses with the haploid egg from the female to form a single diploid cell called the *zygote*.

Having two versions of each chromosome confers distinct advantages: if a serious error is present in a gene, a 'healthy' version of the gene will be present on the other member of that particular chromosome pair. For humans, this holds true for 22 of the chromosome pairs. The 23rd 'pair' is the *sex chromosomes* X and Y. Since girls (XX) have two X chromosomes, a mutation in a gene on one X chromosome can be compensated for by a healthy gene on the other. In boys (XY) having just one X chromosome, mutations in the same gene may have deleterious effects.

For making haploid *gamete* cells the task is to transfer one exact set of chromosomes into each of the daughters of a diploid cell. This takes place by the marvellous process called *meiosis*. One member of each chromosome pair is carefully segregated and assorted so that new complete sets are generated. However, the chromosomes are reassorted, and each haploid cell may, for example, receive chromosome 1, 4, 6, 7, etc. from one of the original sets, and chromosomes 2, 3, 5, 8, etc. from the other set. When a haploid sperm cell is fertilizing an egg, the egg nucleus will contain a full set of chromosomes, but these have also been shuffled during meiosis. Therefore, while the resultant diploid human zygote will have 46 chromosomes, the two full sets will be very different from the sets that were present in the parents. The consequences of all this are profound. Through evolution a number of non-lethal mutations have been collected. Hence, there may be many versions of any given gene.

The protein products of these genes may carry out their intended 'job' somewhat better or worse than average. Different versions of a gene are called *alleles*. The shuffling of chromosomes that carry genes, present as many different alleles, is the basis for the diversity of different traits, characteristics and behaviours within any given species.

Meiosis provides each gene allele with a fair chance of being transmitted to the next generation. That allele will then be expressed together with, and influenced by, all the other genes that have found their way into the nucleus of the same zygote. Then *natural selection* works on the particular combinations obtained. Surviving alleles are then reshuffled by meiosis and distributed into new zygotes. These processes allow a given species to keep and display its full range of variation and possibilities for each new generation. Certain alleles may become more prevalent under certain conditions, but this can be changed to yet another assortment, or reversed, should the niche or ecosystem conditions again change.

Each new zygote is, in fact, a unique experiment. A given gene allele is placed in a nucleus with other genes (in the human case 24,999), many of which it has probably never coexisted with before. Even subtle differences in the time of expression, amounts produced, shape, or resistance to degradation of the encoded protein may generate subtle differences in the abilities of the individual, for better or for worse. This gives the species the fundamental property of variation: on the whole, the capacity to adapt to new ecological niches or to dramatic changes in the total environment.

The overall goal, transmission of genomes from one generation to the next, is the same for asexual and sexual organisms, though for the latter the genomes are handed over to immature offspring. Hence, the *nurture* of offspring becomes important for the survival of the offspring, up to their reproductive age. Plants secure their fertilized ovules with hardy seed coats and fruit tissues. Social insects produce classes of non-reproducing 'workers' to protect and feed a reproducing queen; others carry their larvae in their mouths to save them from destroyed nests. Vertebrates have also developed an amazing array of behaviours to assure the survival and maturation of their progeny.

4.1. Eternal or mortal?

The matter of sex was omitted from our account of how multicellular organisms evolve all kinds of specialization by expressing different sets of genes in different sets of cells. It may, however, be argued that sex was a prerequisite for multicellularity to evolve.

The animal zygote proceeds to cleave into two cells, and then four and then eight. Each cleavage generates daughter cells that stay together as a developing embryo. Thereafter, they start to specialize. If we focus on one of the cells in the eight-celled embryo, we see a cell that switches on a certain set of genes. In the sixteen-celled embryo, the focused cell becomes two daughter cells containing the protein products of the switched-on genes, and these products switch on a second subset of genes. In the thirty-two celled embryo, the proteins of the second subset initiate a signal transduction cascade that induces the by now four daughter cells of the same lineage to move together to a common location. Following this, the lineage may, after additional cleavages, move into the interior of the embryo by a process called gastrulation. Following gastrulation, the lineage contains 512 daughter cells, and they have different fates. Sixty-four of the cells at one end of the embryo activate a set of genes that tells their daughters to differentiate into gut cells. Eight cells near the midline activate genes that start the development of a heart, and so on.

Early on during this *embryogenesis*, some cells switch on sets of genes that order them to become *germ line cells*, precursors of the sperm and egg cells that are uniquely capable of carrying out meiosis. They migrate into what will become the animal's *gonads*, and remain dormant there until sexual maturation of the individual. Then they begin to carry out meiosis in order to produce haploid gametes.

The germ line cells and the remaining, *somatic*, cells have split the job of staying alive and becoming a permanent part of evolution. The germ line transmits the genome to the next generation, while the somatic cells negotiate between the individual and the ecosystem for optimizing the chances of the germ cells to be transmitted: The germ line is protected in the gonads and is released only at appropriate times. The somatic cells are the ones that pump blood, grow muscles, sprout feathers, are aware of dangers, find a good sex mate, and release the sex cells, after which a life cycle is completed. Some organisms die shortly after reproduction (e.g. annual plants, many insects, salmon) and some do not (e.g. humans).

Once there is a life cycle with a germ line and a soma, immortality is handed over to the germ line. This liberates the soma, the individual, to focus on strategies and evolve behaviours for getting the gametes transmitted. Since *morphogenesis* is the key strategy for negotiations with the environment, multi-cellular eukaryotes have evolved all the beautiful and marvellously complex morphological structures we can observe. All the parts of an organism contain cells than retain two full copies of the genome. All the parts work together to ensure the transmission and the nurture of the germ line, and then they vanish, i.e. die.
Death is a part of life already from early embryogenesis. Some cells have been programmed to die. The limbs of human embryos initially terminate as blunt stubs. Then sets of cells die in order to create separate fingers and toes. In every deciduous tree, each autumn the cells at the base of each leaf obey the determination that they should die to cut off the flow of nutrients, and the leaves themselves die. These events are governed by *apoptosis*, a sort of very precisely coordinated cell suicide.

The more general fate of the organism is that the whole soma dies. Natural death may occur after only a few days of life, as with dragonflies. However, death may also be postponed for hundreds of years, e.g. as with sequoia trees. If we do not die by accident, infection or cancer, we die because of age. Our somatic cells die after a certain number of cleavings. Cancer cells, however, are characterized as 'immortalized'. They carry somatic mutations in key cell cycle regulating genes so that they do not stop dividing, either in the body or in laboratory cell cultivation trays.

5. Speciation and Biodiversity

New biological species arise through the process of *speciation*. Organisms segregate into groups that will or will not mate with one another. Segregation leads to the use of new resources, habitats and niches. Traits adapt and evolve under natural selection in order to improve conditions for the organism to live in, e.g. a new forest habitat. This new habitat, however, consists mainly of other organisms (trees) that also evolve to improve *their* conditions. Hence, organisms interact and coevolve. On one hand, segregation leads to *expansion of niches*, and to development and refinement of traits. Any successful development is picked up by natural selection and not diluted after reproductive isolation. On the other hand, competition for limited resources leads to a *compression of niches*, i.e. *specialization.* Specialization reduces competition and lets more species coexist. The outcome of the natural evolutionary processes is the unfolding of more and more complex organisms, and also the generation of *biodiversity* (Figure 1.2).

The origin of *new species* is far from being fully understood, but the outcome is known. Members of a new species fail (by definition) to generate fertile offspring when placed in contact with related species. Why? Because an important barrier is created: sexual behaviours have changed, because the sperm can no longer fertilize the egg, or because the embryos fail to develop properly, and die.

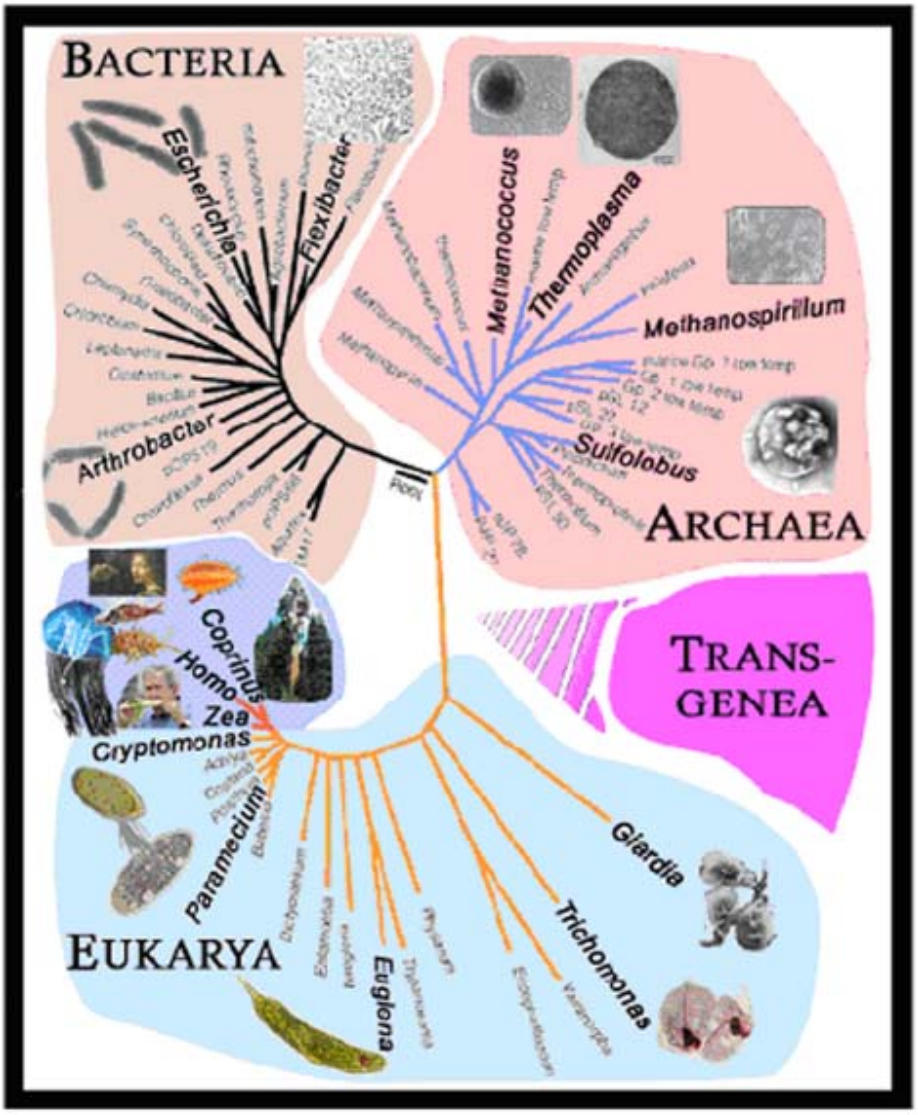

Figure 1.2. Domains of Life as viewed from the dimension of DNA relatedness. In this image, all forms of life existing on planet Earth are shown in their mutual relationship. Longer lines connect more distantly-related organisms, and each of the known domains of life is included in a different colour (Archaea, Bacteria, Eukarya, and Transgenea, representing the new domain created by transgenic manipulation of living organisms). The largest majority of living organisms are invisible (light blue and three purple domains). Only a fraction (red lines, darker blue) represent organisms that are visible, and therefore included in human economic, political and cultural affairs. The purpose of this image is to develop a device and method to visualize all domains of life, including those invisible to most humans, over large geographical dimensions. Of particular interest is the visualization of the novel domain formed by transgenic organisms (GMOs), which have several different ancestries. (Reproduced with the kind permission of Dr. Ignacio Chapela, UC Berkeley)

6. Concluding Remarks

On a larger scale, the outcome of evolutionary development, the incredible biodiversity of more than 1.5 million named species, is known to some degree, but the underlying processes, including the origin of the first organisms and the evolutionary diversification, are more or less a complete mystery to us. Even with the organisms that we study today with all the methodology available,

including the '-omics' techniques (see Chapter 8), we have to admit: the central core of the living is not at all well understood. We cannot explain how gene regulation starts; we cannot explain the differentiation in multicellular organisms, nor the coordinated timing of gene expressions that secure the homeostasis of organisms. In the last few years it has become evident that horizontal gene transfer (HGT) has been much more important for the evolution of life on Earth than earlier realized. Transgenesis-based genetic engineering represents enforced HGT, insertional mutagenesis, possible epigenetic changes and unpredictable chromatin aberrations (see Chapters 1–5, 9, 12–14). The only thing we know is that we do not know. If we realize and accept this, how can we dare to interfere in fundamental and unpredictable ways with ecosystems that have evolved by laws largely unknown to us during the course of 4.5 billion years?

7. Resources

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