7 Evolution

When we are looking for intelligent life outside the Earth, there is a fundamental question: Assuming that life has formed on an extraterrestrial planet, will it also develop toward intelligence? As this is hotly debated, we will now describe the development of life on Earth in more detail in order to show that there are good reasons why evolution should culminate in intelligent beings.

From the time at which the Earth became hospitable enough for organic chemistry to function, the formation of the first cells took only a few hundred million years, while the development of higher life forms, such as multicellular organisms, required an additional 3 billion years. Only recently did the highly evolved and very complicated nature of eukaryotic cells become fully appreciated, together with the realization that the enormous timespan, during which the Earth was populated by single cells only was not a period of stagnation, but actually witnessed a surprising pace of persistent development. Based on the creation of highly specialized organs, made possible by multicellularity and centralized control from the cell's nucleus, the development of intelligent life took another 800 million years. This evolution is driven by two fundamental processes: mutation and natural selection, as described by *Darwin's theory.* While the first of these processes is a pure chance event, the second is directional, since there is usually a very good reason why an organism survives in a given environment.

7.1 Darwin's Theory

Every living organism on Earth fights for its existence (food, light, territory, and shelter) and for its successful reproduction. This effort is called the *struggle for survival.* In this battle, only the most successful organisms survive, a fact that is termed *natural selection.* An additional fact of life is that in the process of reproduction there are *mutations*, caused by changes of the DNA. Mutations are unavoidable and occur at random. They are caused both by the environment (chemicals, radiation, and energetic particles) and by internal processes (faulty DNA replication). Darwin's theory (or principle) states that mutated organisms compete in the struggle for survival, with the consequence that, by natural selection, new, more efficient life forms appear. As the less capable individuals get outcompeted by the more efficient organisms a group evolves towards a population with more efficient members.

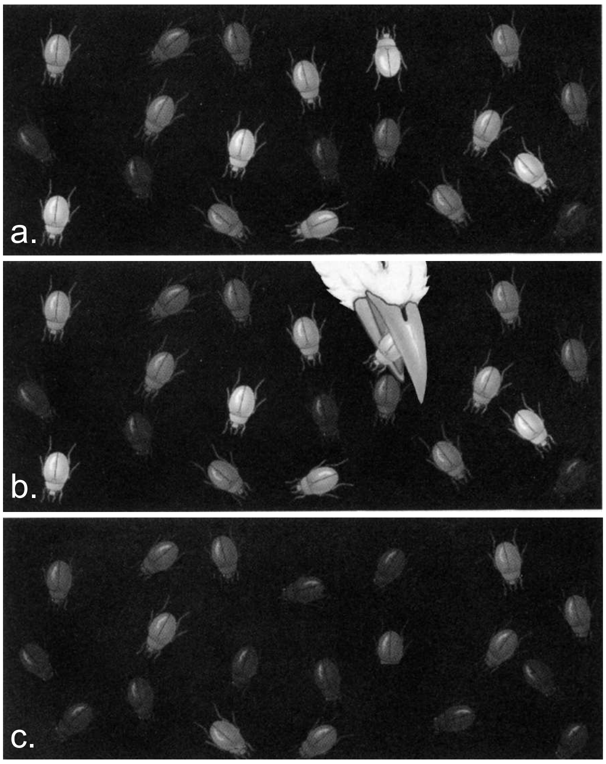

Fig. 7.1. a. – c. Progressive change of a group of bugs that live in a dark environment due to natural selection. Because of the preferential predation on the more easily seen white bugs the group evolves towards a darker population (after Bennett et al. 2003)

The effect of natural selection on a population of bugs living in a dark environment is illustrated in Fig. 7.1. By random mutation individual bugs have different genes for coloring; the available genes of the bug population is called *gene pool*. As white bugs are more conspicuous in front of a dark background they are preferentially caught by predators and their genes are eliminated. Since the dark bugs have more success to pass on their genes to the next generation the gene pool becomes that of a darker population. Although the predation depends on chance meetings of predator and prey the preference of selection is due to the laws of nature, in this case color contrast and visibility.

This example illustrates that Darwin's theory describes a powerful and basic physical process that lies at the core of the biological evolution. Note that the selective advantage of different organisms (e.g. to be dark in the above example) does not need to be large. Because evolution has lots of time available, even rather small advantages can eventually lead to the dominance of the favored species. Because any efficient process outperforms an inefficient one, Darwin's theory not only applies to the evolution of biological organisms, but was already at work in the prebiotic world, where it influenced chemical evolution.

There presently is a heated debate among evolutionary biologists, physicists, and chemists about the long-range effects of Darwin's theory (for a more detailed discussion, see Sect. 7.17). Does the directional aspect of the "survival of the fittest" predict the eventual emergence of intelligence? Or is the directional quality of Darwin's theory only valid over a short range? The answer to this question can probably only be found experimentally: by careful studies of the natural (physical, chemical, and environmental) reasons why the successful organisms survived, and by simulations. Since we are looking at terrestrial evolution in order to learn about the behavior of extraterrestrial life, it is these natural reasons governing evolutionary developments that are the most interesting, because they will also determine the path of evolution on other planets. This chapter therefore concentrates particularly on the question of *why* biological evolution on the Earth happened in the historically documented way.

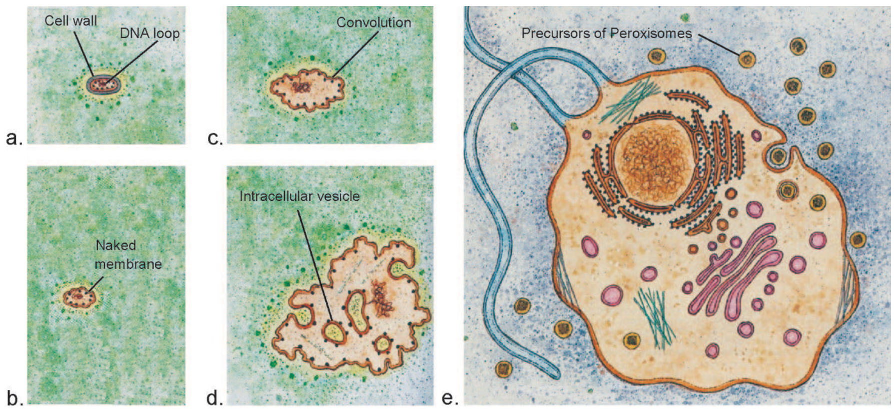

Fig. 7.2. The evolution of the eukaryotic cell (drawn to the same scale) (after de Duve 1996)

7.2 The Development of Eukaryotes and Endosymbiosis

We have seen in Chap. 6 that there are three major branches of prokaryotic cells that separated very early on from a common ancestor, the Last Universal Common Ancestor. Sequencing indicates that the eubacteria and archaebacteria separated first, and that subsequently the ancestor of the eukaryotes, the Urkaryote, split from the archaebacteria (Fig. 6.12). This Urkaryote was in almost all respects still a typical prokaryote, and like these, to provide rigidity and protection, had a cell wall, on the inside of which a single ring-shaped chromosome was attached (Fig. 7.2a). There was a long process of evolution from this simple prokaryotic cell to modern eukaryotic cells with their organelles, sets of chromosomes in a nucleus, and the processes of mitosis and meiosis, during which the cell volume grew by a factor of 10 000. According to de Duve (1996), this development happened in the following stages.

Prokaryotic cells feed by shedding digestive enzymes into their surroundings and subsequently taking up the processed food through the surface membrane (Fig. 7.2a). The first step in the evolution of eukaryotes was probably that the cell lost its wall and was enclosed only by a soft deformable membrane, by which the feeding process was made easier (Fig. 7.2b). By extensive folding of this membrane, shown in Fig. 7.2c, the cell subsequently increased its surface area. Since the amount of matter that can be absorbed increases with the surface area, the cell could take up more food. In addition, in these folds the digestive enzymes became less diluted and thus ensured better processing. The more efficient food handling allowed the cell to grow even larger. Eventually (see Fig. 7.2d), the cell learned to pinch off the inward folds of the membrane to create vesicles (vacuoles) into which food (bacteria) could be swallowed wholesale and treated with undiluted enzymes. Thus eukaryotic cells could take up food both from the outside membrane and from the inside vacuole, and became very efficient hunters.

About 2 billion years ago, an eubacterial predecessor of the organelles, which had been captured in a vesicle, succeeded in avoiding digestion and remain as a guest in the eukaryotic cell. By making itself useful for its host, a symbiotic relationship started (Fig. 7.2e). This was the first of many *endosymbionts*, which from that time onward were able to gain access to the eukaryotic cell and became their organelles. The first organelles were very likely the fibers and microtubules that gave the cell rigidity, and the flagellae, the whip-like projections that propel them in the liquid surroundings (see also Fig. 6.8). The peroxisomes came next, and afterwards the mitochondria. Finally, the cyanobacteria arrived, which brought the plastids that carry out photosynthesis in eukaryotic plant cells (see Fig. 6.12). The use of endosymbionts greatly improved the efficiency and power of the eukaryotic cell.

During this time, between the stages shown in Figs. 7.2d and 7.2e, but probably starting as early as 2.5 billion years ago, another fundamental step