From Belief to Facts in Evolutionary Theory

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Initiated by Charles Darwin's famous book *On the Origin of Species* the theory of biological evolution originated in the middle of the nineteenth century and was enthusiastically accepted by a great number of scientists but at the same time instantaneously confronted with strong opposition by the Church and other parts of the scientific community. Religious people saw a fundamental conflict between the biblical act of creation and evolutionary theory, which is still alive in parts of the United States. The religious opposition in Europe grew even stronger when man was integrated in the evolutionary concept in Darwin's *On the Descent of Man*. A heavy dispute started around the question whether evolutionary change is gradual and slow, as stated by the evolutionists, or occurs stepwise and triggered externally by some catastrophic events. In science the opponents of Darwin's principle of evolutionary optimization through variation and selection raised the claim that this concept of evolution is based on mere tautology and is not falsifiable. It allows only for explanations *a posteriori* and thus cannot make predictions. This criticism has been uphold against evolutionary biology for very long time too and even ve?ry famous philosophers like Sir Karl Popper considered Darwin's theory as non-scientific therefore.

More than one hundred sixty years after the *Origin*, evolutionary theory has changed its appearance entirely: (i) The mechanism of inheritance, completely unknown and wrongly guessed by Charles Darwin, is now fairly well understood, (ii) As chemistry has been rooted in physics by quantum mechanics in the first half of twentieth century, biology has been tied into chemistry by the development of biochemistry, structural biology, and molecular genetics, and the processes going on in cells and organisms are now seen from a completely new chemical perspective, (iii) Darwinian optimization was found to occur also in cell-free molecular systems where it can be studied in great detail by the same techniques as commonly used in physics and chemistry, (iv) Darwin's mechanism was found to be only one of several principles that determine the course of biological evolution and macroscopic evolution is seen now as a exceedingly complex overlay of many influences, and (v) Biological evolution comprises epochs of gradual development as well as instances of punctuation. In the lecture an overview of the current state of the art in understanding biological evolution from a molecular perspective will be given.

1. Introduction

On November 24, 1859, a book entitled *On the Origin of Species by Means of Natural Selection* appeared at John Murray publishing house in London. The first edition was sold out instantaneously and a second edition followed on January 07, 1860. The author Charles Robert Darwin had very well prepared for the publication of his book (Ruse 1979). Several of his scientific friends and colleagues had read parts of the manuscript and a joint paper with Alfred Russel Wallace on natural selection as well as an abstract of Darwin's book were available. The reaction of the Victorian English society on the *Origin* was overwhelming. Strong and emotional

W. Löffler, P. Weingartner (Hg.), *Knowledge and Belief. Wissen und Glauben.* S. xx–yy.

rejection by clergymen, philosophers as well as a certain fraction of scientists and laymen was opposed by partly enthusiastic acceptance by people who were favorable to the idea of species evolution. Surely, a few days after the publication there was practically no educated person in England, who had not heard of Darwin's book and who had not made up his or her opinion on this topic. In particular, the issue of changing species was immediately transferred to the descent of man and Darwin's concept was mostly called 'The ape theory'. Only half a year after the *Origin* had been published, the English public was already involved in a heavy debate that culminated at the meeting of the British Society for the Advancement of Science held in Oxford in June, 1860. It was a major event as a report states: 'the room was crowded to suffocation long before the protagonists appeared on the scene, seven hundred persons or more managing to find places'. One of the main speakers was Bishop Samuel Wilberforce who had written a review on the *Origin* (Wilberforce 1860). In the heated discussion with the zoologist and paleontologist Thomas Henry Huxley Bishop Wilberforce asked, whether Huxley thinks to be related to the monkeys through his grandfather or through his grandmother. The reply of Thomas Huxley to the bishop's question is legendary: 'would I rather have a miserable ape for a grandfather, or a man highly endowed by nature and possessed of great means and influence, and yet who employs these faculties and that influence to the mere purpose of introducing ridicule into a grave scientific discussion—I unhesitatingly affirm my preference for the ape'. This well-known story, whether true or invented, characterizes the hostile relation between the Church and the community of evolutionists in the nineteenth century. It is worth mentioning that doubts were raised against the seriousness of this report without, however, challenging the vehemence of the dispute (Brooke 1991).

2. Theory of evolution, science, and religion

The basic principle of Darwin's natural selection is straightforward and easily explained: Selection occurs between different variants within a species and operates in finite populations. The number of descendants is measured in terms of fitness values, which measure the mean numbers of descendants that reach the reproductive age. Different variants, in general, have different fitness values. Selection is very powerful: An increase of only 10% in fitness values, corresponding to a mean progeny of eleven rather than ten descendants, is sufficient to replace a less fit variant by a fitter one within some hundred generations. Successively, all variants in the population except the fittest one are eliminated. Artificial selection differs from natural selection just by the intervention of animal breeders or plant growers who decide about fitness of variants. Prerequisites for natural or artificial selection are (i) populations of multiplying individuals, (ii) existence of variants with different fitness values, and (iii) finite resources sustaining finite populations only. Whenever variants are formed in a population selection will occur and thus species are subjected to steady change. Two populations of the same species may diverge when they are in different habitats. After sufficiently long time the two populations may reach a degree of divergence that justifies identification of two different species. The three key ingredients in the Darwinian scheme of evolution are:

(i) *Variations* occurring spontaneously and not produced by the environment,
(ii) *Competition* for resources so that only the best adapted survive to reproduce, and, therefore
(iii) *Selection*, by the environment, of which variants will survive and increase in number.

In the *Origin* Darwin discusses a great number of carefully selected examples for his concept and suggests its general validity. Branching and extinction of species results in a branching-tree view of evolution, rather than a step-ladder of progress, or a series of isolated 'species creations'. The ultimate consequence of the Darwinian theory of evolution is the existence of a *'tree of life'* defining the relations of all species, the current ones as well as the extinct.

Darwin's theory of evolution had vehement proponents: The naturalist Alfred Wallace and the zoologist Thomas Huxley, who have been mentioned already, the botanist Joseph Hooker and many others, among them also clergymen. The ideas received support from two scientists, who were characterized by Michael Ruse as 'borderline evolutionists': the geologist Sir Charles Lyell and the astronomer John Herschel. It is important to mention that the concept of evolution understood as a process changing species originated already in the eighteenth century. Among the supporters of this idea were Charles Darwin's grandfather, Erasmus Darwin, Chevalier de Lamarck, and Etienne Geoffroy.

Most of Darwin's contemporaries in science who were strongly opposing the theory of evolution focused on the variability of species and insisted in their invariance. These people were religious and wanted to see scientific knowledge in verbal agreement with the text of the Bible. They were more or less influenced by Geoge Cuvier's concept of global catastrophes, for example the Great Deluge described in the Bible, which wiped out the ancient species that we find as fossils nowadays. Darwin's contemporaries who supported invariance of species were the paleontologist and geologist Jean Louis Agassiz, the paleontologist Richard Owen, the geologist Adam Sedgwick, and the moral philosopher and polymath William Whewell. Their vehement reaction against Darwin's theory originated from the correct concern that his concept is providing the key for the transformation of the idea of evolution from speculation to science. In their view invariance of species was required for the harmony of theology and science. Bishop Samuel Wilberforce has expressed this very clearly in his statement: 'The principle of natural selection is absolutely incompatible with the word of God. [It] contradicts the revealed relations of creation to its Creator'. In addition, Charles Darwin and his scientific friends saw man as part of the animal kingdom, which was clear heresy in the eyes of nineteenth century theologians.

Why was there a hostile climate close to real warfare between the evolutionists and the representatives of Church in the nineteenth century compared to the cultivated and rather friendly dispute in the second half of the twentieth century? I think the answer is based on two facts: (i) In the nineteenth century religion had still large overlap with science; all old universities started from a theological faculty after all and philosophy, school of law, medicine, and science were branching off slowly over centuries. The same is true for the overlap of science and society which was gradually weakened during the twentieth century because of increasing diversification and abstraction in the scientific methodology, and (ii) both, science and religion have reduced their claims: After the theory of evolution had become an established discipline within science the evolutionists became more modest and open for the interaction with other ideas and concepts. As initiated by Agassiz already, Cuvier's catastrophes became a subject of serious scientific investigations and their historical reality has been verified. Three examples are mentioned here: (i) A large meteorite falling into the gulf of Mexico at the cretaceous-tertiary boundary about 65 million years ago has presumably caused mass extinction of dinosaurs. (ii) Melting of an ice barrier of ancient Lake Agassiz, which had covered the major parts of Manitoba from 10000 B.C. to 6000 B.C., has reshaped the river system east of the Rocky Mountains. (iii) During the last glaciation the Black Sea was a lake and the Black Sea basin has been filled after that through periodic water flows between itself, the Caspian Sea, and the Mediterranean. These singular events have left their traces that can be currently investigated and reconstructed with high precision and high sensitivity analytical techniques. On the other hand, the representatives of all major Christian Churches have made their peace with the idea of evolution and do not insist in the verbal interpretation of the Genesis. Creation is seen as a unity and biological evolution is one of its unfoldings.

Still, the coexistence of modern evolutionary biology and religion is not completely free of friction as Michael Ruse points out in his recent book *Can a Darwinian be a Christian?* (Ruse 2001). The dispute goes on in the twenty-first century and as I shall comment at the end of this essay, it is both necessary and useful to continue the discussions in the light of modern life sciences. The United States saw also an unfruitful and special development that is not shared by Western Europe: Almost militant opponents of the idea of evolution in the American society make the request that a 'Science of Creation' in the spirit of the nineteenth century is taught simultaneously with evolutionary biology at school (For details see National Academy of Sciences 1999).

3. Genetics and the theory of evolution

A theory or a model of inheritance that comes close to our current understanding is completely missing in Darwin's concept of evolution. It seems also that he had no idea by which mechanism variations of existent organisms could arise. It is an irony of history that almost simultaneously with the spectacular publication of the *Origin of Species* the correct mechanism of inheritance was discovered in the Austrian-Hungarian Empire by the monk Gregor Mendel. His works were published in local Academy Proceedings and the evolutionists ignored them completely. Gregor Mendel's discovery consisted of a true and twofold revolution in biological thinking: First, he introduced the concept of statistics into the evaluation of experiments. Different from most botanists of his time he had received an education in mathematics and physics during his studies. Regularities of events, which become evident only when many observations are considered simultaneously, were not regarded relevant in nineteenth century biology. Second, Gregor Mendel postulated that properties are inherited in packages, one coming from the mother and one from the father, respectively. His 'atoms of inheritance' nowadays called genes were thought to replace the dominant idea of gradual blending of parental properties in the offspring. The idea of 'atoms' reflecting discreteness of nature was a truly revolutionary concept. Indeed, thirty years later Ludwig Boltzmann had still difficulties to convince his contemporaries in physics that the concepts of atoms and statistics of events are appropriate to describe the nature of matter.

Although Mendel's work was neither completely ignored nor forgotten between 1866 and 1900—a few botanists mentioned it—the evolutionists, however, never referred to it. The so-called rediscovery of Mendel's work at the turn from nineteenth to twentieth century initiated a heavy and long lasting fight between evolutionists and geneticists. The former dismissed mutations as the ultimate cause for variation and the latter were at odds with the gradualism and continuity. Gregor Mendel's rules are now taught at school as an indispensable part of evolutionary biology. Mendelian inheritance is a rather drastic but appropriate abstraction since the reality is much more complex, as it is always in nature and particularly so in biology. Nevertheless, Mendel's discovery is an illustrative example of brilliant and powerful reduction: By choosing the proper system—color and shape of the fruits of peas—and by carrying out the right experiments—controlled fertilization of the plants—he was able to reduce the complex genetic mechanism to a set of rules. In the light of present day molecular biology we can understand the origin of these simple rules as a limiting case and we are able to interpret and predict correctly the experimentally found deviations from the rules.

4. From population genetics and the synthetic theory of evolution to molecular biology

The first successful attempt to reconcile genetics and natural selection was made by the theoretical population geneticists Ronald Fisher, John Haldane, and Sewall Wright. They developed a mathematical model of Mendelian inheritance and combined it with the selection principle. An interesting historical detail is relevant for a correct picture of the personality of Ronald Fisher. During most of his scientific life he tried steadily to belittle the discovery of Gregor Mendel and he accused him of having polished his data and of having been unaware of the importance of his discovery. Today, the achievements of both, Mendel and Fisher, are highly appreciated by the scientific community.

Between 1930 and 1950 the population geneticists successfully developed a detailed and comprehensive mathematical theory that allows for modeling evolution of genotypes in populations. In the center of this concept are the genotypes or the genomes to which fitness values are assigned as empirical parameters. The organism commonly called phenotype is not considered explicitly in this concept and epigenetic factors are largely neglected. Population genetics provided several useful metaphors. Evolution, for example, is considered as a walk of populations or species on an abstract fitness landscape. Since the selection principle implies that the mean fitness of a population is a non-decreasing quantity the evolutionary walk on fitness landscapes is bound to proceed uphill or to stay on level sets.

Starting before the beginning of World War II biology entered a novel period through the ultimate unification of genetics and evolutionary theory (Mayr 1982) in form of the synthetic or Neo-Darwinian theory. Many biologists were active in this centennial endeavor, which can to an end in the late nineteen-forties. As prominent representatives for others we mention here only Theodosius Dobzhansky and Ernst Mayr. Natural selection was fully reconciled with genetics, mutation and recombination were correctly recognized as the sources of variation. The Darwinian principle of evolution was extended to behavioral strategies in animal societies (Maynard Smith 1982; Wilson 1975) and led to a new discipline called sociobiology. The publication of Wilson's book initiated a kind of revival of the debate between evolutionary biologists and sociologists in the second half of nineteenth century (For a collection of essays to this topic see Caplan 1978). Now, almost thirty years after the beginnings sociobiology has become an established field and the originally heated discussions have ceased.

The exciting discoveries of the molecular structures of the most important biomolecules, proteins and nucleic acids, initiated the new and rapidly growing area of molecular biology (Judson 1979), which branched off the already well-established field of biochemistry. Methods from physics and structural chemistry were applied to investigate the molecules of life, their interactions, and their functions in cell and organism. Building upon the rich knowledge of physiological chemistry and biochemistry molecular biologists started an incredible and almost explosive process of data accumulation and detailed insights into living matter that has not come to an end yet. The first spectacular achievements in the nineteen fifties were the determination of the three-dimensional molecular structures of proteins by John Kendrew and Max Perutz and deoxyribonucleic acids (DNA) by Francis Crick, James Watson, Maurice Wilkins, and Rosalind Franklin. Both studies showed that molecular functions can be inferred from known structures by means of conventional knowledge from molecular physics and chemistry. The body of knowledge on biomolecular structures was and is steadily growing and at present structural biologists are able to interpret the function of large aggregates like cell organelles or complete virus particles from their spatial structures. No before long, it seems, we shall be in a position to understand and derive properties and functions of whole cells from the known structures and interactions of their molecular constituents. Application of structural knowledge to human medicine opened new routes to the development of pharmaceutical compounds and provides novel tools for softer and subtler therapies. A new branch of industry called biotechnology originated.

5. Molecular genetics, the ‘tree of life’, and neutral evolution

Fast progress in the development of techniques to decipher the genetic messages stored in DNA provided access to sequences of whole genomes from viruses and bacteria to man. To give an idea of genome sizes: Viruses commonly have sequence lengths of a few thousand nucleotides—or digits of the genetic alphabet—bacteria contain a few million, and the human genome consists of about three billion digits. Knowing the sequence of a genome is only the first step and current molecular genetics aims at the full exploration of all biomolecules derived from genomic DNA. The current development goes towards a quantitative or ‘systems’ biology whose goal is to understand, model, and predict all cellular processes together with regulation and control in multi-cellular organisms.

Darwin had sketched a ‘tree of life’ in his *Origin*, which represents the historical course of the descent of species. Evolutionary biologists in the nineteenth and the first half of the twentieth century reconstructed this tree by means of morphological characteristics. Present day organisms were compared with the fossilized remnants of ancient species. Interpretation of the fossil record together with current forms yields phylogenies that are combined to the tree of life. Comparison of protein or DNA sequences provides an additional and independent access to the history of the biosphere. The reconstruction of phylogenies from sequence data of homologous molecules in different species was initiated almost simultaneously with the availability of the first amino acid sequences in proteins. Later on sequencing of nucleic acids turned out to be much cheaper and easier than the sequence analysis of proteins and hence, DNA sequences became the primary source for the reconstruction of phylogenies. Nowadays, whole genomes can be compared to build phylogenetic trees. Thousands of biomolecules, which were derived from common ancestors, have been identified. Genetic sequences turned out to be much less conserved than originally expected. Evidence was found for so-called 'horizontal' gene transfer—this is transfer of genetic information between species. Horizontal gene transfer implies that genes in the same organism may have different histories and thus obscures the tree-shaped vertical transmission of genetic information. Horizontal gene transfer is particularly frequent with bacteria and there it is responsible for the spreading of resistance against antibiotics.

The comparison of sequences revealed that the majority of mutations are selectively neutral in the sense that selection does not discriminate between the parent molecule and the mutant. Motoo Kimura developed a variant of population genetics, which is based on neutrality and called it the theory of 'neutral evolution'. The wealth of sequence data available at present fully confirmed the concept of neutrality and led to the following view of evolutionary optimization: (i) The majority of mutations is selectively neutral and creates a reservoir of mutants of roughly equal fitness, (ii) selection discriminates against deleterious variants and eliminates them from the populations, and (iii) rarely occurring advantageous mutations determine the course of the optimization process. The apparent predominance of neutral mutations gives rise to the phenomenon of a molecular clock of evolution: Strictly speaking, the molecular clock hypothesis assumes that the number of mutations depends only on the time elapsed and the size of the genome. In other words, the rate of mutation per year and nucleotide is constant and allows for measurement of time on an evolutionary scale. Precise measurements have shown that the molecular clock is an abstraction with systematic and random deviations in real biology. One the other hand, the concept is useful and valuable for estimates when no other data are available. Because of approximate constancy the molecular clock has been used successfully for dating times of divergence of species and phyla (Kumar and Hedges 1998).

6. Evolution experiments in the laboratory and *in silico*

The spectacular progress in understanding biomolecules and their functions through the development of molecular biology raised the desire to design molecular assays that allow for direct observation and prediction of evolutionary phenomena. In the nineteen sixties Sol Spiegelman initiated *in vitro* studies on evolution by injecting proper ribonucleic acid (RNA) sequences of viral origin into a replication assay. He observed optimization of the rate of replication through mutation and selection. His experiments showed that evolutionary phenomena are not restricted to cellular life. Ensembles of nucleic acid molecules when transferred into proper environments show the same behavior as populations of cells or organisms do. Spiegelman's experiments ended the tautology debate about the theory of evolution: Starting already in the nineteenth century the concept of evolution was considered non-scientific and not falsifiable by some philosophers because 'survival of the fittest' is a mere tautology if fitness cannot be determined independently of the fact of survival. This misconception became virulent again in the epistemology of Karl Popper. In Spiegelman's experiments fitness is completely defined in terms of measurable rate constants of biochemical reactions and thus is determined independently of a selection experiment. At the same time Manfred Eigen formulated a concept of evolution that combines knowledge from chemical kinetics and molecular biology and allows for a quantitative description of selection, mutation, and optimization in both, molecular ensembles and populations of organisms (For a comprehensive presentation see Eigen and Schuster 1979; a popular English version is found in Eigen and Winkler-Oswatitsch 1993). Eigen's kinetic theory of evolution has been successfully applied to quantitative descriptions of Spiegelman's evolution *in vitro*.

Selection experiments *in vitro* have been supported and extended by computer simulations (Fontana and Schuster 1998; Crutchfield and Schuster 2003). The major insight into evolutionary optimization that was gained by these studies concerns the role of neutral mutations. The landscapes on which evolution takes places are very rugged in the sense that they contain many local fitness optima on all levels. Comparison with terrestrial landscapes yields the metaphor that the fitness landscapes look like the Dolomites rather than like Mount Fuji. Populations, climbing a rugged landscape with the restriction of a non-descending walk mentioned above, would not reach very high summits but would soon be trapped in minor peaks. The spaces underlying fitness landscapes are of high dimensions and what seems to be a peak in one dimension may be a horizontal ridge in a perpendicular one. Such sets of points forming 'horizontal' manifolds have the same fitness and they are neutral with respect to selection. Whenever uphill climbing ends on some point, this point is part of a neutral manifold along which the population drifts randomly until it reaches another area where higher points exist and where uphill optimization can be continued. As seen also in evolution experiments the optimization process is a sequence of short adaptive or uphill periods interrupted by long quasi-stationary epochs of constant mean fitness. Thus, neutral mutants are not only a by-product of the molecular mechanism of mutation, they play an important role in making evolution more efficient in the sense that higher local fitness optima can be reached.

7. What the Darwinian scenario cannot explain

Despite apparent success in the interpretation of optimization through variation and selection, the Darwinian principle is unable to provide descriptions for all phenomena observed in biological evolution. Among other problems there are major evolutionary transitions, which escape an explanation by Darwin's concept (Maynard Smith and Szathmáry 1995). These major transitions in evolution remind of the ladder theory of the biosphere, since each transition opens access to a new hierarchical level. Such major transitions are:

(i) the transition from independent RNA genes to an integrated genome,
(ii) the origin of the genetic code as a prerequisite for the transition from an RNA world to a DNA(+RNA)+protein world,
(iii) the formation of the cell with metabolism and compartment structure,
(iv) the formation of the complex eukaryotic cell through endo-symbiosis of two or more prokaryotes,
(v) the formation of symbiosis between species,
(vi) the transition from unicellular to multi-cellular organisms,
(vii) the transition form solitary animals to animal societies,
(viii) the transition from animal societies to primitive human societies, and
(ix) the development of the present human societies with language and writing.

All major transitions share one common feature: They lead from a lower hierarchical level to the next higher and they are accompanied by an increase in complexity. In general competitors at the lower level are integrated into a synergetic unit characterized by cooperation of previously competing elements. A mechanism for such an integration called the ‚catalytic hypercycle' was proposed already in the nineteen seventies (Eigen and Schuster 1979). Like a theme with variations the hypercycle is still the only model that describes transitions from lower to higher levels of complexity in mechanistic detail.

Competitors become mutually dependent through catalysis during the formation of a hypercycle. Closure of the catalytic chain forming a cycle leads to a unit with novel properties and functions. The new acquired properties, however, are not only accessible to the members of the hypercycle, they can be exploited also by individuals that do not contribute to the common wealth. These semi-autonomous individuals, characterized best as parasites, gain even a selective advantage. In order to survive exploitation the new unit has to develop boundaries separating members from parasites. Such boundaries can be of physical nature like membranes, skins, city walls or frontiers between states. Only such boundaries allow for controlled exchange with the environment. There are also normative boundaries like codes, signals, behaviors, conventions, languages and writing allowing for recognition of members of communities. Biology shows that every major transition was accompanied by the development of expensive control mechanisms for the detection of parasites. On the other hand, individuals exhibiting defective behavior can also be observed at each level. We give here a few representative examples.

Viruses are genes or groups of genes that multiply within their host organisms but escape the host's control and leave in order to infect new still healthy cells. Viruses multiply under exploitation of the resources of the host cells, which in turn have to develop complex defense mechanisms in order to survive. 'Selfish' or 'jumping genes' are pieces of DNA reminding of viruses. They remain within the cell but proliferate faster than the rest through autonomous replication mechanisms. Transformed cells are individual cells that escape growth control in the multi-cellular organism. They may cause growth and proliferation of malign tumors and one important task of the highly complex immune system of vertebrates is to detect and annihilate such autonomous cells before they jeopardize the organism. Animal societies protect themselves against exploitation though the invention of all kinds of recognition signals that can be used to detect defecting individuals. The highly complex human societies, finally, developed an expensive and comprehensive control system to detect and eliminate asocial individuals.

8. The role of ethics and theology in modern life sciences

The rapid progress in understanding the mechanisms of life and reproduction opened the doors to entirely new branches of science and different kinds of technological and medical applications. Molecules can be designed for predefined purposes in material science, pharmacology, and medicine. The genetic repertoire of organisms can be changed and enlarged by means of genetic engineering. Genetic engineering of bacteria is a common tool in biotechnology. Genetically engineered plants become more and more common in first world countries. Therapeutic exploitation of human genetic engineering could provide cure for genetic diseases from rather common diabetes to very rare but severe genetic failures. Cloning of animals was successful in several cases and seems to provide access to domestic animals with new properties. Experiments with stem cells give otherwise hard to obtain insights into the mechanism of cell differentiation and are considered as a proper source to grow tissues in cultures that can be used in surgery to repair or replace malfunctioning organs. The development of science and technology in these areas has been so rapid that citizens could not follow at the same pace. Most of the new experimental techniques touch or penetrate into areas of society that are under taboo. Interfering with human reproduction conflicts with almost all religions. No wonder that people are full of uncertainty and fear uncontrollable consequences originating from modern life sciences. Emotional discussions in the societies give rise to non-uniform laws and often very different restrictions for experiments and usage of the products produced by the new technologies. Here, I feel society moves in the manner of a dangerous random walk through a kind of ethical vacuum and *terra incognita*. One of the greatest challenges for ethics and theology is to help politicians and other citizens to harmonize society and modern life sciences.

References

Brooke, J.H. 1991 *Science and Religion—Some Historical Perspectives*, Cambridge: Cambridge University Press.

— 2001 *The Legend in Need of Revision?* Lecture delivered at Emmanuel College, Cambridge, February 26, 2001.

Caplan, A.L. (ed.) 1978 *The Sociobiology Debate*, New York: Harper and Row.

Crutchfield, J.P. and Schuster, P. 2003 *Evolutionary Dynamics. Exploring the Interplay of Selection, Accident, Neutrality, and Function*, New York: Oxford University Press.

De Beer, G. 1964 "Mendel, Darwin, and Fisher", *Notes and Records of the Royal Society of London* 19, 192–226.

Eigen, M. and Schuster, P. 1979 *The Hypercycle—A Principle of Natural Self-Organization*, Berlin: Springer.

Eigen, M. and Winkler-Oswatitsch, R. 1993 *Laws of the Game: How the Principles of Natural Govern Chance*, Princeton: Princeton University Press (Translation of the German edition: *Das Spiel—Naturgesetze steuern den Zufall*, München: Piper 1975, by Robert and Rita Kimber).

Fontana, W. and Schuster, P. 1998 "Continuity in Evolution. On the Nature of Transitions", *Science* 280, 1451–1455.

Judson, H.F. 1979 *The Eighth Day of Creation*, London: Jonathan Cape.

Kumar, S. and Hedges, S.B. 1998 "A Molecular Timescale for Vertebrate Evolution", *Nature* 392, 917-920.

Maynard Smith, J. 1982 *Evolution and the Theory of Games*, Cambridge: Cambridge University Press.

Maynard Smith, J. and Szathmáry, E. 1995 *The Major Transitions in Evolution*, Oxford: W.H. Freeman—Spektrum.

Mayr, E. 1982 *The Growth of Biological Thought. Diversity, Evolution and Inheritance*, Cambridge / MA: The Belknap Press of Harvard University Press.

National Academy of Sciences 1999 *Science and Creationism. A View from the National Academy of Sciences*, 2nd Edition, Washington / DC: National Academy Press.

Ruse, M. 1979 *The Darwinian Revolution*, Chicago: The University of Chicago Press.

— 2001 *Can a Darwinian be a Christian? The Relationship between Science and Religion*, Cambridge: Cambridge University Press.

Wilberforce, S. 1860 “Review of *On the origin of species*”, *Quarterly Review* 1860, 225–264.

Wilson, E.O. 1975 *Sociobiology—The New Synthesis*, Cambridge: Harvard University Press.
