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Teaching evolutionary biology at schools and universities

Importance and perspectives

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Even Charles Darwin and Alfred Russel Wallace puzzled over the adaptive significance of the zebra's striped coat. Perhaps the pattern confused predators, so that lions, for instance, were no longer able to identify individual prey with any certainty when running at high speed? Another theory suggests that the pattern might deter parasites such as the tsetse fly.

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Teaching evolutionary biology at schools and universities

Importance and perspectives

Foreword

“Nothing in biology makes sense except in the light of evolution.” This insight, which the evolutionary biologist Theodosius Dobzhansky imparted to American biology teachers in an essay written in 1973, has lost none of its relevance today; quite the contrary. The importance of evolutionary biology has increased steadily in the intervening years, not least as a result of new technical developments in the field of molecular biology.

Evolution is an omnipresent and highly dynamic process. Ideas and insights based on the theory of evolution often overlap with our everyday lives, such as our management of infection. When scientists advise doctors to prescribe fewer antibiotics, this is based on an observation from evolutionary biology: that the frequent use of antibiotics is accelerating the emergence of resistant strains of bacteria. That is why evolutionary biologists and medical doctors are joining forces to discuss new ways of delaying the development of resistance and to discover why some pathogens, such as the Zika and Ebola viruses, are suddenly producing variants which represent a threat to human health. Evolutionary biologists and oncologists are also currently developing new approaches to the treatment of cancer. But it is not just medicine which benefits from the important stimuli coming from evolutionary biology. The commonalities which exist between the theory of evolution and economics in game theory provide a perfect example of transdisciplinarity.

It is the aspect of natural history in particular which makes evolutionary biology indispensable to our general education. Where does man come from? What is it that makes him unique? What influence does culture have on evolution? It is a central recommendation of this paper that the concepts underlying the theory of evolution should therefore be included in the school curriculum at a much earlier stage and addressed more comprehensively.

We are greatly indebted to the Volkswagen Foundation for setting up a funding line for the specific purpose of developing the profile of evolutionary biology at a number of universities and putting the necessary financial support in place. The German National Academy of Sciences Leopoldina is keen to build on this initiative and focus attention on the major importance of this subject to school and university education, as well as to research. I trust that this paper will provide a suitable impetus for this, and that you will find it a stimulating read.

Prof. Dr. Jörg Hacker
President
German National Academy of Sciences Leopoldina

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Summary and recommendations

1. Biological evolution is the unifying, overarching explanatory principle of the life sciences. Evolutionary biology provides humans insights into perception of themself, their relationship with the environment, their health, their social interactions, their economic dealings, and their cultural development. That is why a knowledge of the basic tenets of evolutionary biology on the development of life on earth combined with a deeper understanding of the mechanisms and dynamics of evolutionary processes, are absolutely fundamental to the teaching of natural sciences at schools and universities.

2. Although some improvements have been made in recent years, a considerable disparity still exists between the importance of modern insights of evolutionary biology and how the subject is taught at German schools and universities. The status of evolutionary biology at German universities declined in the decades following the Second World War due to the misappropriation under National Socialism of what were purportedly laws of evolutionary biology. As a result, research in the field was temporarily disconnected from international developments, and teaching content was not updated sufficiently. So as far as research and teaching in the subject is concerned, there is a need for a fresh start to be made at universities by recruiting appropriate staff and setting priorities.

3. The recommended course of action for attaining a general improvement in the teaching of evolutionary biology involves adopting a coordinated approach to the status quo in schools and universities. Such a strategy would have three main objectives: (1) to survey comprehensively the current status of education in evolutionary biology and support positive trends, (2) to establish evolutionary biology in the curriculum and in teacher training as an integrative framework for the teaching of biology and (3) to promote evolutionary biology as being fundamental to the life sciences and as a transdisciplinary research programme at universities.

4. A curriculum which sets out the role of evolutionary biology as a binding framework and a common thread running through the modern life sciences, as well as the overarching principle which explains their very nature, is an important instrument for achieving a long-term transformation of school biology lessons which recognises the central scientific and practical importance of evolution. There must also be an opportunity to study evolutionary biology under aspects of philosophy of science, thus allowing scrutiny of the intrinsic nature of the natural sciences. To this end, illustrative examples from evolutionary biology must be coupled with corresponding proposals for experiments and learning through research at school. The introduction of such a curriculum should be prepared with and accompanied by teaching materials which adopt concept-based and empirically verified teaching models to convey the key issues of modern evolutionary biology. They should be able to respond quickly to scientific developments and address selected target groups. Special efforts are required to update textbooks more rapidly to incorporate new scientific findings, especially through the use of electronic media.

1. Evolution as an epistemological principle of modern biology

Evolution is the unifying, overarching explanatory principle of biology. Evolutionary biology describes the development of life on earth, and shows how the interaction between the principle of natural selection and random processes has shaped biological diversity and is continuing to bring about dynamic change. Evolutionary biology examines the fundamental processes which lead to ecological adaptations and new species, as well as the rules which govern the interaction of organisms, including humans, and the formation of social systems. The fundamental laws of evolution are also of general significance for economic and social human activites. These areas will be discussed in detail below, starting with the historical development.

1.1 From Darwin to modern evolutionary biology

There are only a handful of theories which have triggered a scientific revolution and have profoundly shaken up the world view of modern civilisation.[1] One such was Charles Darwin and Alfred Russel Wallace's[2] theory of evolution.[3] The key mechanism which they proposed, namely the process of natural selection, supplied a purely scientific explanation for the way in which organisms have adapted to their environment and for the diversity of species which exists. At the same time, understanding this mechanism is a prerequisite for understanding the historical development of organisms on earth. This includes the realisation that humans too are a natural branch of the family tree of life on earth, and has been – and continues to be – shaped by evolutionary mechanisms just as much as every other species.

The fundamental principles of evolutionary biology

The main insight of evolutionary biology is that adaptation to new environmental conditions can arise from a combination of random genetic variation and natural selection (Tab. 1 – Selection). Apart from natural selection, another important mechanism of evolutionary change is neutral evolution (Tab. 1 – Drift). The majority of molecular changes in genetic material (DNA) can be explained by neutral rather than by selective mechanisms. Selection always affects the characteristics and/or appearance of an organism (its phenotype), and this is the product of a developmental and biological process. Environmental factors can also affect the properties of the phenotype (Tab. 1 – Variation).

1 Evolutionary biologist Ernst Mayr describes the repercussions of Darwin's theory in his essay *Darwins Einfluss auf das moderne Weltbild* (2000). Link: http://www.spektrum.de/magazin/darwins-einfluss-auf-das-moderne-weltbild/826771 (as per: 10.1.2017).

2 The general public associates the theory of evolution almost exclusively with Charles Darwin. And there are good reasons for this, as Darwin devoted more of his life to the theory than anyone else, and collated the best examples. But in fact Alfred Russel Wallace was developing a very similar theory contemporaneously with Darwin, and told the latter about it in a letter. Both theories were presented in public for the first time at a session of the Linnean Society in London in 1858.

3 This position statement uses the terms 'theory of evolution' and 'evolutionary biology' interchangeably. This is done with the intention of showing that not only did subsequent biological research support the theoretical reflections of Darwin and Wallace; their ideas were also developed further on the basis of crucial new evidence.

Table 1: Fundamental principles of evolutionary biology

Principle	Explanation
Relatedness	Common descent of living organisms due to a shared phylogeny. Evolutionary changes occur only through the modification of existing lines.
Variation	Diversity of the formation of a characteristic within a species. A distinction must be drawn between (1) genetically determined variation, which results from random mutations and genetic recombination, and (2) modification where the variation is caused by environmental factors (phenotypic plasticity – not genetically determined or, in the case of epigenetic variation, only heritable to a limited degree).
Fitness	Genetic variation results in different genotypes, which determine reproductive fitness. Many factors can influence whether or not a genotype with its alleles is represented in the gene pool of the subsequent generation. These include how well-adapted the individual is to its environment, its ability to find a mate, and the relative number of offspring.
Selection	Individuals which are better adapted to prevailing environmental conditions (adaptation) are more likely to survive to sexual maturity and thus have an advantage when it comes to reproduction (natural selection). In the event of a change in environmental conditions, there is a directed change in the frequency of alleles in the gene pool of a population. Environmental factors which affect reproductive success are called selection factors.
Drift	Random variation in the frequency of alleles in the gene pool of a population. Drift is a consistent feature of every generation, but is more pronounced in smaller populations and across many generations. It forms the basis of neutral evolution.

Although evolutionary adaptations and changes are constantly taking place, they are not biased towards a particular or specified direction. This does **not** imply a continuous progression from the primitive to the complex, or from the simpler structure of an organism to a more complex organisational form.[4] The concept of 'survival of the fittest' coined by Darwin is often misunderstood as meaning the 'survival of the strongest' rather than of the best-adapted. Although the fundamental principle of the selection mechanism appears very straightforward (Variation -> Selection -> Adaptation), it can give rise to a large number of sometimes highly complex consequences. The question of the optimal solution of conflicts (e.g. in respect of ecological resources, between the sexes, or between hosts and parasites) has become a core topic of modern evolutionary biology. Here, evolutionary biology overlaps with economics, which studies optimisation and conflict resolution within economic processes.

Milestones of evolutionary biology

Evolutionary biology did not end with Darwin and Wallace, but continued to make important strides in the years thereafter (Fig. 1). This included, for instance, integrating genetic concepts with those from evolutionary biology ('modern synthesis'). The population genetics which emerged from this, developed the 'neutral theory of evolution'[5], and research efforts expanded into social interactions and cooperation mechanisms. These developments lead also to a mathematisation of evolutionary biology which changed the field from mostly observational research towards working out conceptual theoretical principles and new theories. This phenomenon is in

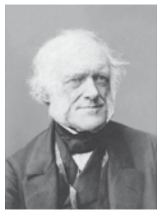
4 In his book *Full House- The spread of excellence from Plato to Darwin* (1996), Stephen Jay Gould describes very cogently why there is no intrinsic mechanism for progress within natural selection.

5 Kimura (1983).

Milestones in evolutionary biology

1830 to 1850

The evolution of life as a historical sequence



The development of stratigraphy and the classification of fossils by Charles Lyell (photo) led to an understanding of geological processes, and allows to document a timeline of biological evolution on earth and to gain an insight into the llarge time scales involved.

1858

Natural selection as an evolutionary mechanism

The mechanism of natural selection proposed by Charles Darwin (photo) and Alfred Russel Wallace provides a scientific explanation for the adaptation of organisms to their environment and the gradual unfolding of life.

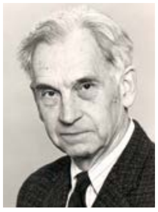
from ca. 1910

Population genetics and microevolution

The laws of inheritance, recombination, mutation and selection in populations are formulated as mathematical equations. The principles of population genetics are the basis for understanding the differentiation of populations (microevolution) and the origin of species.

1940 to 1950

Modern synthesis



During the modern synthesis, the principle of natural selection became combined with the insights from Mendelian genetics, population genetics, taxonomy, morphology and palaeontology. The German biologist Ernst Mayr (photo), who emigrated to the USA, was an important figure in the development of the modern synthesis.

from ca. 1960

Evolutionary strategies

The benefit of cooperation as opposed to interests of the individual constitutes a fundamental evolutionary conflict which extends from the evolution of multicellular organisms to the development of social systems and commercial relationships between people. The concepts of game theory are used to study the dynamic nature of this conflict (Chapter 1.4.5).

1960 to 1980

Behavioural biology and sociobiology

Behavioural biology examines the interactions between individuals and the development of social systems in which the interests of the individual conflicts with those of the group. It shows also a basic conflict in the interests of the sexes.

from ca. 1970

Neutral evolution

Motoo Kimura from Japan (photo) develops the principles of neutral evolution with the help of mathematical approaches and simulations. This shows that the evolution of DNA and protein sequences is mainly a result of neutral rather than selective mechanisms. A molecular clock can be deduced from this, which in turn allows us to reconstruct family relationships between species at a molecular level. Neutral evolution serves as an essential null hypothesis which enables us to trace back the course of selection processes.

from ca. 1980

Gene-environment interaction

The form and function of an organism are influenced not only by genetic factors, but also by environmental ones (plasticity). This can be described statistically, and forms the basis for our understanding of evolutionary adaptation. The molecular mechanisms associated with this are described by epigenetics. Acquired epigenetic mutations can be passed on in part to subsequent generations, and thus influence adaptations.

Fig. 1: Milestones in evolutionary biology. The illustration traces the development of the most important phases and concepts in evolutionary biology

some respects comparable with the development of quantum theory in physics; i.e. a theoretical component emerged as a discipline of evolutionary biology in its own right. This became a burgeoning new development in evolutionary biology from the mid-20th onwards. However, in Germany this development was originally missed. Following the misrepresentation of evolutionary biology by the National Socialists (especially as regards race ideology), biologists in Germany focused their attention elsewhere during this concept building phase in evolutionary biology. As a result the subject played only a subordinate role in university teaching and research. The consequences of this can still be felt today in the current school curricula. It is only with some hesitation that new research findings are included in the curriculum and in teaching media, and thus introduced into school lessons. As far as higher education is concerned, gradual efforts have been made during the past fifteen years to correct this trend, but this has not yet been achieved extensively across all faculties.

1.2 Humans as a product of evolution

Darwin's book *On the origin of species* quickly became a hot topic of conversation among the general public after it first appeared in 1859. The reason for this was that crucial insights about the evolution of humans could also be extrapolated from his theory.[6] It was basically indisputable that humans too were a part of the evolutionary continuum, and were thus subject to speciation processes, even if Darwin addressed this question explicitly only in a later work, namely *The Descent of Man, and Selection in Relation to Sex* (1871). This came at that time in parallel to an already existing discussion on whether people could be categorised as having reached different stages of development, depending on their race. As a consequence Darwin´s theory was misappropriated again and again for political purposes.[7]

The biological evolution of humans

Modern evolutionary biology and palaeontology have since supplied us with a much clearer picture of human genetic variations and origins (Fig. 2). Unlike human's nearest relatives – the chimpanzee and the gorilla – the molecular line leading to humans represents only a single long branch, which diversified only recently. On the other hand, fossils provide evidence of branches in the line towards modern humans which once existed but are now all extinct, most recently the line of Neanderthals. These branches still exist in the case of gorillas and chimpanzees, with the split sometimes occurring far back in time (as represented by the depth of the triangles in Fig. 2). Indeed, gorillas and chimpanzees are typical of most species in this respect. But humans have lost these relatives. Hence, while we distinguish sub-species and races for most other species, the current human line is so young that a subdivision into such categories is not applicable.

The direct forefathers of present-day humans (*Homo sapiens*) emerged not much more than about 10,000 generations ago from a comparatively small original population. That is why all humans today still share nearly 90 percent of all genetic variation. People from Europe or Africa, for instance, differ by no more than 10 percent in terms of these variants.[8] This means that a given European individual can be more related to an individual from Africa than to a Europe-

6 Rather to Darwin's chagrin, however, this took the form not so much of a scientific discussion as of a populist controversy.

7 Charles Darwin was an avowed opponent of slavery. The idea that all men had the same origins and a common ancestor was one of the motivating factors behind his formulation of the theory of evolution; cf. Desmond & Moore (2009).

8 Li et al. (2008).

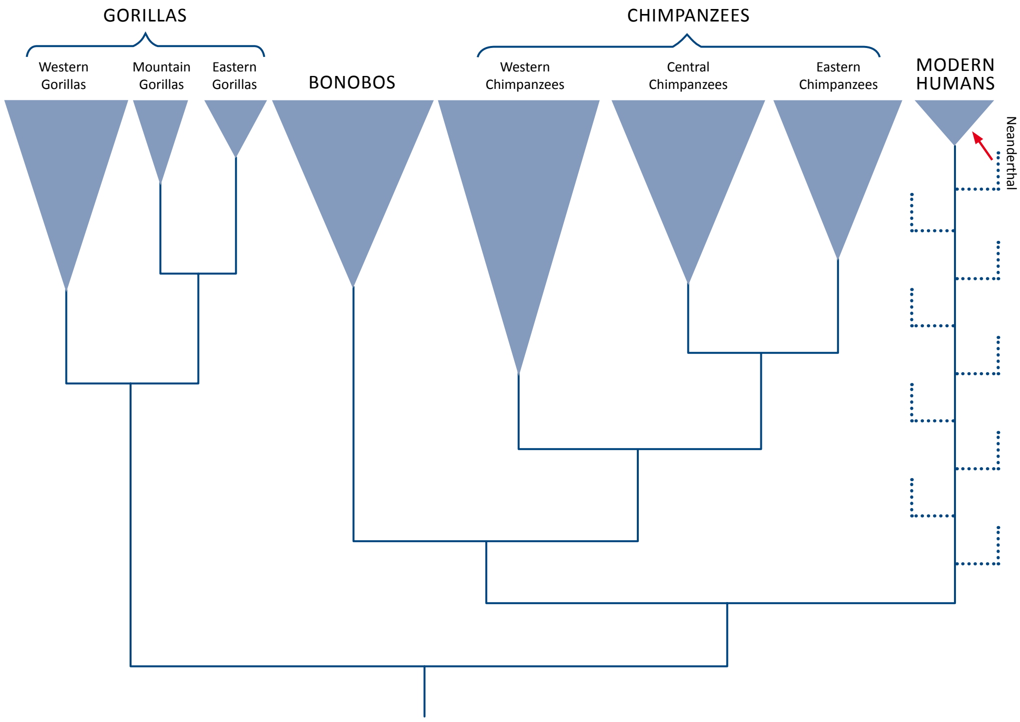


Fig. 2: Comparison of the genetic diversity of humans with that of his nearest relatives, the gorillas and chimpanzees. The breadth and depth of the triangles is a measure of the relative molecular diversity and evolutionary age of the lines which exist today. The illustration is not drawn to scale. Humans and the chimpanzee diverged at least 7–8 million years, and possibly even more than 13 million years ago.[9] However, modern humans only began to evolve in about the last 200,000 years. This means that every person living today is a descendant of a very young line and is related fairly closely to everyone else. Older and more diverse branches (shown as dashed lines) are now extinct, with only fossils to prove their existence – such as for instance Australopithecus or Neanderthal man. However, before dying out, Neanderthals exchanged genes with human populations which had migrated from Africa (red arrow). The illustration is based on that of Gagneux et al. (1999).

an neighbour. In other words, people are all very similar in terms of genetics; their gene variants can be interchanged without difficulty. Consequently, classifying people by race, by whatever criteria, has no foundation in evolutionary biology. In particular, there are no indications of any supposed ranking of the races. Nor indeed would such a ranking make sense for any other naturally occurring species. The term race and its relative value makes only sense in the context of artificial breeding stocks, e.g. to describe expected agricultural yields for a plant or relative milk production for a cow. Also the often-used concept of a ‘pure blood line’ only makes sense if it is applied to artificial breeding stocks, but not to natural living organisms and especially not to people.

These new findings about the genetic similarities of all people are still far too little understood in the public domain. This allows authors of books, for instance, to continue to peddle misleading information about race, whether overtly or subliminally.[10] If the general public was better informed about modern evolutionary biology, this might help ensure that such claims were dismissed out of hand as false.[11]

The cultural history of humans

We are also learning an increasing amount of detail about the cultural history of humans. In recent years, the appli-

9 Langergraber et al. (2012), Venn et al. (2014).

10 This includes the books of Thilo Sarrazin (2010) *Deutschland schafft sich ab* and Nicholas Wade (2014) *A troublesome inheritance.*

11 Regardless of the evidence provided by evolutionary biology, it is important to note that human dignity and human rights are not based on genetic considerations, but apply to each and every one of us.

cation to archaeology of methods used in molecular biology has led us to make surprising discoveries about anthropology and human cultural history. The analysis of ancient DNA has been at the focus of this research, i.e. the use of technology to isolate genetic material from bones up to 400,000 years old.[12] This genetic material from bones or, indeed, teeth, makes it possible for us, for instance, to establish the ability of earlier humans to digest dairy products or starch, and thus to better understand their lifestyle.[13] Population genetics allows us to tell from our analyses of ancient DNA how people migrated from Africa to Europe and the other continents, and whether – for instance – the representatives of settled cultures drove out hunters and gatherers.[14] The teeth also contain traces of pathogens responsible for plague and tuberculosis. It should be possible to reconstruct the history of these pathogens on the basis of genetic analyses.[15] Understanding the evolution of viruses and bacteria and how they interact with the human immune system is of crucial important for healthcare today, and especially for the containment of emerging pathogens.

Apart of the biological evolution of humans, the cultural and social development of humans was also studied much since back in the 19th century. This has given rise to multi-faceted and sometimes controversial schools of thought, which have however often lacked sufficient insight into biological evolution. It is generally the case for humans that cultural advances can emerge and undergo selection within a single generation, making change considerably more rapid than with biological evolution. In this respect, humans became somewhat disengaged from their biological evolution, whilst at the same time representing a crucial new factor for the evolution of all other organisms.

1.3 Humans as an evolutionary factor

Humans are not merely a product of evolution, but have themselves influenced the development of the biosphere in the course of colonising the entire globe. Today, one finds evidence of human's impact on ecosystems in nearly every single habitat.[16] The destruction of habitats, the dissemination of invasive species, increased nutrient discharge into the soil and water, higher concentrations of carbon dioxide in the atmosphere and the associated acidification of the seas and rise in average temperatures are altering living conditions and thereby trigger evolutionary processes in many species of plants and animals as well as in microorganisms.[17]

Climate change, globalisation and evolution

Climate change and globalised trade are promoting the worldwide relocation of plants, animals, fungi and microorganisms, and the introduction and/or migration of new species to areas where they are not indigenous. These newcomers bring foreign pathogens with them and often compete directly with native species. They, can therefore exert a powerful evolutionary pressure on other species.[18] Some of the new arrivals, such as for instance Himalayan balsam and giant hogweed, are so ecologically adaptable and so successful in evolutionary terms that they can dominate entire habitats within a few years and displace the original biocoenosis.[19] A deep understanding of the evolutionary and biological basis for

12 Krause & Pääbo (2016).
13 Curry (2013).
14 Haak et al. (2015).
15 Culotti (2015).
16 The Nobel Prize Laureate Paul J. Crutzen coined the term 'Anthropocene' for our new geological age; cf. Crutzen (2002).
17 Settele et al. (2014).
18 Moran & Alexander (2014).
19 Vilà et al. (2010).


Fig. 3: Central European blackcaps (left) usually overwinter on the Iberian peninsula and in northern Africa. However, in recent decades some have been flying to England or Ireland in the autumn instead, lured there by the mild climate (yellow areas). These different migratory routes may lead to a divergence of the species – an example of rapid evolution (cf. Rolshausen et al. (2009)). The blue areas indicate the traditional overwintering areas of blackcaps from elsewhere in Europe. Photo: Gernot Segelbacher

such invasions helps us to prevent and manage them, which is important for both nature conservation and agriculture.[20]

The change in average temperatures in central Europe has also direct repercussions on species of flora and fauna. To give just one example, climate change has resulted in a species of bird, the European blackcap (Fig. 3), to change its migration pattern. Its populations used to leave their breeding areas in southern Germany and migrate en masse to Spain and North Africa to overwinter. For some time now, it has been possible to observe how some individuals have started going their own way – in both senses of the phrase. A proportion of the population from southern Germany now travels to England in the autumn and overwinters there. Since these individuals have less distance to travel, they return from their winter quarters in the spring about two weeks earlier than the others. Once they arrive in the breeding area, they mate with other birds which have spent the winter in England, as potential reproductive partners from their traditional winter quarters have not even returned yet. If this trend perpetuates itself, the example of the blackcap demonstrates how different lengths of migration arising from the use of different overwintering destinations might eventually give rise to new species.[21]

Mosquitoes as disease vectors

Climate change is also turning central Europe into a habitat for animal species which are probably in the early stages of adaptation. Particular attention is being paid to several exotic species of mosquito, as these can transmit a number of diseases.[22] The Asian tiger mosquito (*Aedes albopictus*), individual specimens of which have been found in Germany in recent years, is a carrier (vector) of tropical diseases such as dengue fever, chikungunya and yellow fever in its original distribution area. Tests there have shown that, for the virus to reproduce in the mosquito, the temperature must not drop below 20° C.

20 In Germany, twenty of the most predominant non-indigenous species of flora and fauna generate costs of roughly Euro 156 million p.a.; cf. Federal Environment Agency (2003).

21 Bearhop et al. (2005).

22 Schaffner et al. (2013).

Even though there are already indications that Asian tiger mosquitoes have overwintered at several locations in southwest Germany, there is no current expectation that the pathogen could become established in Germany. Nonetheless, a careful eye should be kept on the evolutionary biology and ecology of the tiger mosquito and other vectors.[23]

Human interventions as a selection factor: evolution triggered by fishing practices

There is plenty of evidence to show that humans are now the greatest driver of evolutionary change, and can therefore be classified as a selection factor in his own right.[24] As well as having an indirect impact on organisms and ecosystems due to factors such as climate change, humans are also having a direct influence on the evolution of species of flora and fauna. In the fishing industry, for instance, the preference is for catching large fish, with the regulation of mesh size allowing smaller ones to escape back into the sea. By stipulating a particular size of fish in this way, humans are interfering in reproductive biology and consequently in the evolution of, say, the cod and sockeye salmon (Fig. 4):[25] individuals which mature earlier and therefore remain smaller can pass through the nets, reproduce more offspring for the next generation, and thereby account for a larger proportion of the population. This fishing practice has resulted in the average size of successive generations of cod becoming smaller in the region around Newfoundland, to give just one example. Sexually mature creatures are now 25 percent smaller than they were in the 1930s.[26]

Fig. 4: The catching of sockeye salmon, in this case in Bristol Bay, Alaska, USA, is restricted to a particular size of fish by the mesh size of the nets. This is resulting in humans having an impact on reproductive biology. One consequence may be evolutionary changes in the size and age of sexual maturity of the fish. Photo: Andrew P. Hendry.

1.4 Applied evolutionary biology

Climate change, disease, food security and biological invasions are pressing social challenges, each of which has an evolutionary dimension. These man-made global problems could be offset at least in part by solutions developed in the field of evolutionary biology. The following paragraphs illustrate the most important areas where such solutions could be applied.

1.4.1 Resistance in agriculture and medicine

The building up of resistance is a textbook example of evolutionary adaptation. Hosts and their parasites are engaged in a non-stop competition to gain the upper hand over their adversary. For example, if a mutation in the host makes it immune to the parasite, the latter will become extinct unless individual parasites develop a new way of circumventing the molecular mechanisms of immunity. This principle of dynamic evolutionary adaptation (also known as the ‘evolutionary arms race') is also a problem in agriculture and medical care. Pesticides and antibiotics are used until individual pests or infectious bacteria build up a resistance, which is then able to spread within the population; usually rapidly, because it goes unchallenged. Eventually the pesticide will become less effective, which is why a new pesticide with a new mode of action will then have to be developed.

23 Kampen (2016).
24 Palumbi (2001), Thomas (2015).
25 Jørgensen et al. (2007).
26 Heino et al. (2002), Jørgensen et al. (2007).

The spread of pathogens and agricultural pests and their development of resistance are becoming increasingly problematic issues for humans (Tab. 2). The general assumption is that insect species will take about ten years to develop variants which are resistant to pesticides through natural evolutionary adaptation.[27] It takes a little longer for weeds to build up resistance: about 10–25 years.

However, bacteria develop resistance most rapidly and with the most serious repercussions for patients. The extreme propagation rates which resistance mutations entail, and the facility with which the DNA of other organisms is taken up into their own genome (horizontal gene transfer), make bacteria highly adaptable. The inappropriate use of antibiotics in human and veterinary medicine is accelerating the development of resistant strains: antibiotics select against non-resistant germs. And it is this very action which allows resistant variants to compete, use the resources which have now been freed up, and spread. Then there are the so-called multi-resistant strains, which none of the antibiotics in common use is able to defeat. Resistance to antibiotics is confronting the healthcare system with serious problems. The European health agency known as the European Centre for Disease Prevention and Control (ECDC) estimates that some 25,000 patients die in Europe each year after being infected with multi-resistant bacteria.[28] In Germany, the number of fatalities resulting from antibiotic resistance is currently estimated at between 6,000 and 15,000 per annum.[29] Antibiotic resistance also results in longer hospital stays and eventually also to higher treatment costs.[30] There is considerable demand for more R&D in the search for new antibiotics, but this can be very time-consuming and expensive. The development process normally takes about 10 years, and the costs have been estimated to be up to one billion US dollars.[31]

Various strategies regarding the use of antibiotics and pesticides have been tested in an attempt to delay the build-up of resistance.[32] Many institutions recommend the more sparing use of antibiotics as a matter of course.[33] At the centre of research today lies the notion of varying the use of different agents both temporally and spatially, so as to prevent or at least delay adaptation.[34] One strategy involves using new antibiotics only in combination with one another.[35] Evolutionary experiments in laboratories are providing important indications about the best way to proceed. For example, a study looked at how the alternate administration of two pairs of antibiotics commonly used in clinical practice affects the bacterium *Pseudomonas aeruginosa*.[36] This hospital bug is often multi-resistant, and can cause life-threatening infections in patients with weakened immune systems or who

27 The Arthropod Resistance Database http://www.pesticideresistance.org (as per: 10.1.2017) is recording all known cases of insecticide resistance; National Research Council (2000), Palumbi (2001), REX Consortium (2013).

28 ECDC (2009).

29 The wide range given for the estimated number in Germany (National Reference Centre at the Charité: 6,000; Federal Ministry of Health: 15,000) and the comparison between the relative estimations of fatalities due to multi-resistant bacteria in Europe (ca. 750 million inhabitants) and Germany (ca. 80 million inhabitants) is indicative of the methodological uncertainties which exist. When considering these figures, it is also important to remember that some patients would probably have died even if the bacteria had not been resistant to antibiotics.

30 Academy of Sciences in Hamburg & Leopoldina (2013).

31 Larson (2007).

32 For an overview of strategies, cf. Kouyos et al. (2014).

33 Academy of Sciences in Hamburg & Leopoldina (2013); DART (2015), Link: https://www.bundesgesundheitsministerium.de/fileadmin/Dateien/Publikationen/Gesundheit/Sonstiges/Bericht_DART_Deutsche_Antibiotika-Resistenzstrategie.pdf (as per: 25.1.2017).

34 Strategies against the development of resistance apply equally to pesticides in agriculture and to antibiotics in medicine; cf. REX Consortium (2013).

35 Academy of Sciences in Hamburg & Leopoldina (2013).

36 Römhild et al. (2015).

Table 2: The years in which antibiotics and pesticides were first licensed, and when the first resistance was observed; cf. Palumbi (2001), CDC (2016). However, the appearance of resistance does not mean that an antibiotic is completely ineffective.

	Year licensed	Year resistance was observed
Antibiotic		
Sulfonamides	1930s	1940s
Penicillin	1943	1946
Streptomycin	1943	1959
Chloramphenicol	1947	1959
Tetracyclines	1948	1953
Erythromycin	1952	1988
Vancomycin	1956	1988
Methicillin	1960	1961
Ampicillin	1961	1973
Cephalosporins	1960s	Late 1960s
Linezolid	2000	2001
Daptomycin	2001	2005
Ceftaroline	2010	2010
Herbicide		
2.4d	1945	1954
Dalapon	1953	1962
Atrazine	1958	1968
Picloram	1963	1988
Trifluralin	1963	1988
Triallate	1964	1987
Diclofop	1980	1987

are chronically ill. As part of the study, evolutionary experiments were conducted in the laboratory under controlled conditions. The rapid alternation of two antibiotics – so-called antibiotic cycling – proved highly-effective against the bug and delayed the development of resistance (Fig. 5). However, other experiments showed that the simultaneous use of two antibiotics can even greatly accelerate the evolution of resistance; in other words, research here is still in its infancy.[37]

Since the development of resistance is a basic process of evolutionary biology, its corresponding theoretical context should be taken into consideration more widely in agriculture as well as in human and veterinary medicine. This is essentially a parasite/host conflict which can be analysed using the methods of game theory (Chapter 1.4.5).

37 Pena-Miller et al. (2013); cf. also Kupferschmidt (2016).

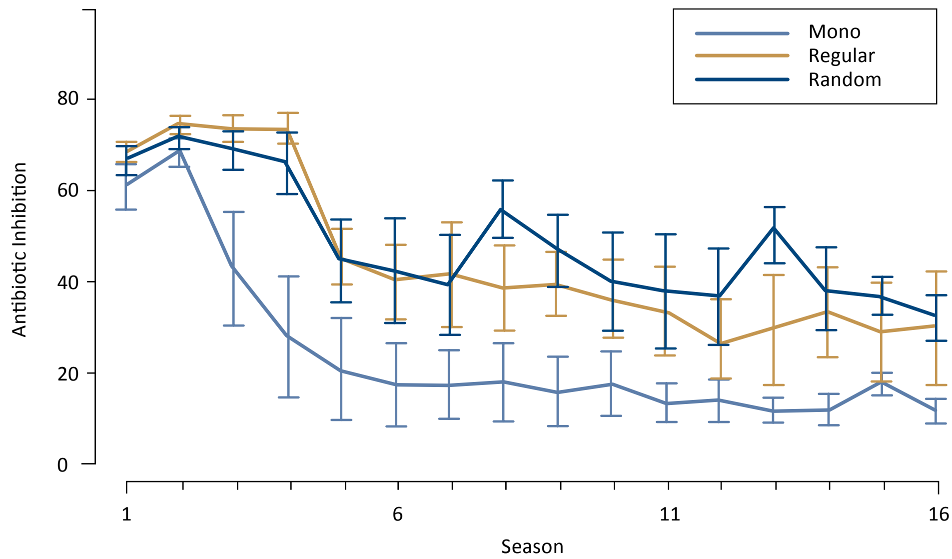


Fig. 5: Running an evolutionary experiment on the development of antibiotic resistance by *Pseudomonas aeruginosa*. Sixteen evolutionary cycles were run, with the administration of a single antibiotic per cycle being compared with a strictly alternating dose of two different antibiotics and a randomly alternating dose. The administration of a single dose led rapidly to a decrease in sensitivity to antibiotics, while the alternating doses delayed the build-up of resistance quite considerably. The curves represent average values, and the variance between replicates is shown by the vertical bars. Illustration based on that of Römhild et al. (2015).

1.4.2 Evolutionary medicine

Humans are a product and part of evolution. Recognising this is very important for healthcare and the treatment of diseases. In the past decade, this realisation has led to a new discipline: that of 'evolutionary medicine'[38] . This tries to evaluate on the basis of the evolutionary history of humans which biological structures and functions, but also which dietary regimes and lifestyles are beneficial to health. This has led researchers to make new discoveries about the development of diseases and treatments. Fundamental to this is the knowledge that human's biology changes much more slowly than his environment or culture. This gap gives rise to lifestyle diseases, which are responsible for much of the burden placed on today's healthcare system.

The organisms alive today took three and a half billion years to evolve. That includes *Homo sapiens* – modern humans – and this evolutionary history is reflected in every one of us. So evolutionary biology also supplies the crucial scientific basis for evolutionary medicine. Looking at things from an evolutionary point of view is incredibly important to our understanding of the nature of humans, be they healthy or sick. But evolutionary medicine of this kind has yet to be enshrined in medical practice or in medical training. Rapid medical advances have been made possible as a result of the human genome project[39] and by research into the genome and into the molecular development of many other species, combined with new ways of analysing how model systems and humans actually function. These discoveries necessitate new structures within which scientific work can be conducted, new kinds of questioning, and the inclusion and/or transferral of this into university teaching and medical practice.[40]

38 e.g. Williams & Nesse (1991), Nesse & Williams (1996), Ganten (2008), Nesse et al. (2010).

39 The human genome project unravelled the mysteries of the human genome between 1990 and 2003.

40 Stearns et al. (2010), Stearns (2011).

Evolutionary medicine views humans in sickness and in health as the end product of its long evolutionary development. There are many examples where biological conditions such as an upright gait and efficient food metabolisation, which had good reproductive survival value for our early ancestors and were therefore selected, have not yet had time to adapt to the way we live today. Whilst it is true that the development of an upright gait made humans a skilful and versatile generalist as a hunter and gatherer, the different lifestyles we live today take their toll in the form of spinal and skeletal disorders. And whilst those who metabolised food efficiently at times of shortages were the survivors, an overabundance of available food means that this evolutionary legacy is now resulting in obesity, cardiovascular disease and diabetes. The evolutionary purpose of the renin-angiotensin system (RAS) was to maintain a good level of blood pressure regardless of the circumstances, through the retention of salt and water. These resources were in short supply in the savannah, the original home of *Homo sapiens*, and humans excreted them through heat, physical labour, and sweat; an active RAS helped them to survive. Our present lifestyles and high consumption of salt mean that the RAS is over-activated, and 50 percent of the adult population are hypertensive. Anxiety, pain, and fever developed originally as defence mechanisms, but are now often deleterious to health.

But humans are also themself a part of evolutionary processes which first existed back in history. For instance, the allele for lactose tolerance in some regions rose from about 0 to 85 percent within a few thousand years after the introduction of agrarian structures and the dairy industry.[41] Lactose tolerance is thus a shining example of the effect environmental changes can have on the targeted shifting of allele prevalences. The great mediaeval plague pandemics also led to shifts in resistance alleles, and a similar effect can currently be witnessed in relation to the development of resistance to AIDS in Africa.

But it is not just as pathogens that bacteria are relevant. All multicellular organisms, humans included, live in close association with a large number of bacteria which are able to assume important functions. This has given rise to the concept of a meta-organism, according to which the individual interacts with its microbiome (the community of microorganisms which colonise a multicellular organism).[42] Research in this field is generating fundamentally new insights into the role of nutrition in health, but also into the growth of allergies and inflammatory diseases of the intestines, lungs and skin (Fig. 6). Thus the development of the immune system is, for instance, dependent on normal bacterial colonisation of the gut. This colonisation is fostered by natural birth and breastfeeding. Children born by Caesarean section and who are exclusively fed formula instead of breast milk are more likely to suffer from asthma, allergies and obesity.

Evolutionary medicine thus promotes a holistic approach to medicine which takes account not only of an evolutionary understanding of biology, but also of the individual's entire biotic and abiotic environment, and how he interacts with this environment.

41 Leonardi et al. (2011), Curry (2013).

42 Bosch & Miller (2016), cf. also the article 'Mensch und Mikrobiom: Mögen die Mikroben mit uns sein!' by Kegel (2016) in the Neue Zürcher Zeitung, Link: http://www.nzz.ch/feuilleton/zeitgeschehen/mensch-und-mikrobiom-moegen-die-mikroben-mit-uns-sein-ld.107915 (as per: 10.1.2017).

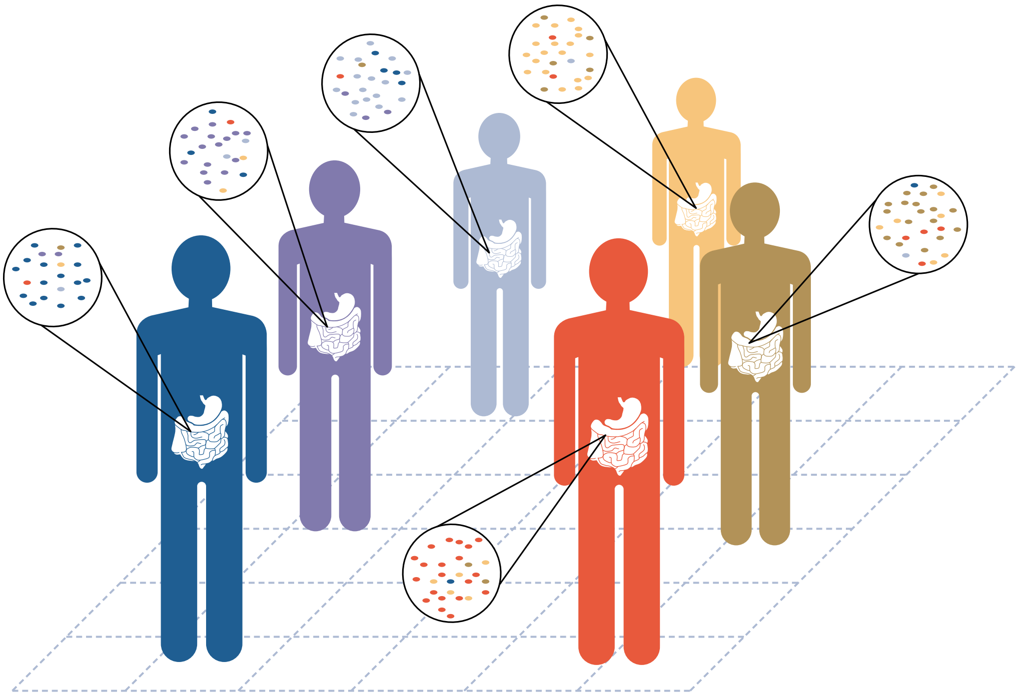


Fig. 6: The microorganisms found in the human gut have a major impact not only on our digestion, but also on our immune system and mental health. Each individual's digestive system has its own distinctive microbial community (shown in the illustration by the colouring within the circles), which comprises many thousand different species of bacteria and has a considerable influence on our general wellbeing. The composition of these bacteria is partly determined by the individual's genetic make-up. Mutations in these genes can disrupt the bacterial community and cause stomach disease, etc. (cf. for instance Goodrich et al. (2016)). Illustration: Philipp Rausch.

1.4.3. Molecular phylogenetics

Phylogenetic research has always been a crucial part of evolutionary biology. The use of molecular methods has enabled it to open up an increasing number of new fields of application.[43] With the help of DNA sequence comparisons, phylogenetic trees can be reconstructed which illustrate, for example, the origins of a flu virus pandemic[44] and which can even, to some extent, allow predictions to be made about future outbreaks. This enables suitable vaccines to be produced in good time. It is also possible to trace back the transmission paths of AIDS viruses and their development of drug resistance. In an ecological context, relatedness analyses can help determine the origin of invasive species and identify populations which require special protection. In medicine, the origin of genetic diseases can be determined (genetic epidemiology). Paternity tests and crime-related forensics[45] also make use of findings and molecular markers developed on the basis of research in the field of evolutionary biology.

1.4.4. Application of evolutionary principles

In an article in the journal *Science* (2014), the US biologist Scott Carroll and his colleagues called for principles of evolutionary biology to be used when tackling such problems as the rapid evolution of parasites, weeds, and pathogens. The authors proposed that political management measures be adopted, such as regulating the use of antibiotics and pesticides at regional level. In order to counteract problems related to climate change, they also recommended that the genetic make-up of

43 Leopoldina (2014b), pp. 29–31.

44 For the origins of the swine flu pathogen H1N1, cf. for example Smith et al. (2009).

45 In the much-publicised case of the 'Bulgarian nurses', it was possible to demonstrate that the respective strain of HIV had already been circulating in Libya for years, and had not been introduced to the country by the defendants; cf. de Oliveira et al. (2006). Forensic phylogenetics can also clarify whether Person A infected Person B or vice versa, which proved important in another court case; cf. Scaduto et al. (2010).

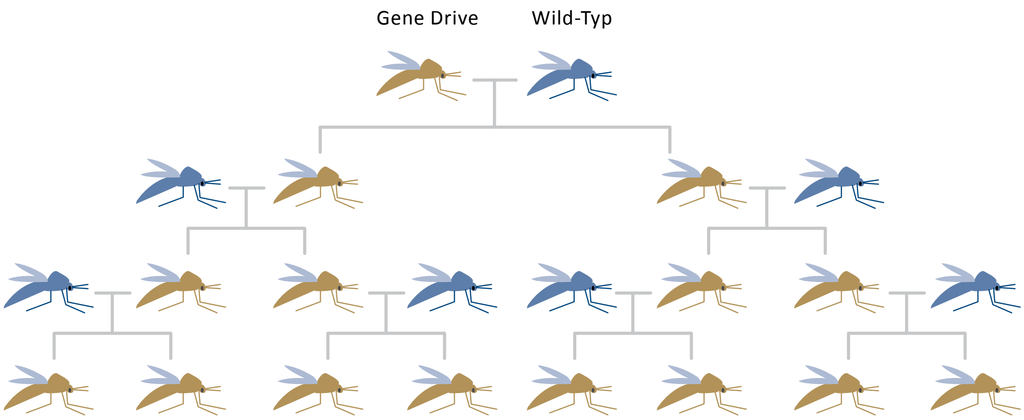


Fig. 7: The principle of the gene-drive system, taking as an example the transformation of a mosquito population. Altered genes are constructed in the laboratory with the assistance of gene scissors, and introduced into a living creature (gene drive). If a treated individual mates, then all of the pair's offspring will receive a copy of the new gene, and pass it on in turn to their descendants until the gene is present throughout the population. If the genetic element also passes on resistance to the malaria pathogen (single-cell parasites of the genus *Plasmodium*), then the mosquito will no longer be able to transmit the pathogen to humans. Illustration based on Esvelt et al. (2014).

plants and animals be altered to improve food production, and that action be taken to confront environmentally-induced chronic diseases, up to and including gene therapy for humans. Particular attention should also be paid to the loss of biodiversity, including the opportunities and challenges presented by targeted breeding programmes for wild animals threatened with extinction. So representatives of evolutionary biology are opening up a political discussion which will require an awareness of evolutionary, biological, medical and economic relationships if the right decisions are to be made for the future.

So-called gene-drive systems are a new application based on evolutionary principles. The genome of an organism is altered with the help of gene scissors in order to produce particular characteristics.[46] Precise intervention allows genetic elements to be generated which duplicate themselves with each generation and can therefore spread exponentially within a population.[47] Genome editing can be used for such purposes as making mosquitoes resistant to the malaria pathogen (Fig. 7).[48]

This method could be used to prevent the transmission of malaria without the need for any significant impact on the intermediate host or the ecological context.[49] The Zika virus[50], which poses an ever increasing risk, could be tackled in the same way. The possible application of such gene-drive systems is controversial, and is currently being discussed by experts and policy advisors.[51] This example shows that the options which can be derived from principles of evolutionary biology are increasingly having extensive repercussions on the practical actions of humans. Consequently, the worlds of politics and society will have to make decisions which can only properly be made with a sound knowledge of genetic, ecological, evolutionary and biological relationships.

1.4.5 Evolutionary game theory in economics and biology

Game theory was originally developed in the field of mathematics, and its applicability was first demonstrated in the

46 Leopoldina (2015).

47 Such elements are referred to in evolutionary research as 'transposons', or colloquially as 'egotistical DNA'.

48 Esvelt et al. (2014).

49 Gantz et al. (2015).

50 First isolated from a rhesus monkey in 1947, the protein and nucleotide sequences of the virus have mutated significantly over the last fifty years; cf. Wang et al. (2016).

51 National Academy of Sciences USA (2016).

context of economic and social sciences.[52] Unlike evolutionary biologists, however, economists expect people to act rationally and with a particular goal in mind. Game theory deals with models of rational action, when two or more protagonists make decisions and the outcome depends on the actions chosen by all of the protagonists. Thus a rational protagonist (an individual or a company) must also bring into his calculations an expectation of what decisions the others will make. In the context of evolutionary biology, the putative selection of strategies is made not by rational decision-makers, but through the natural process of selection; that said, the conflict situations in natural selection are absolutely comparable with decision-making in economy. As a result, the two scientific fields have greatly enriched one another. The 'Nash equilibrium' of game theory has its equivalent in the 'evolutionarily stable strategy' (ESS) of evolutionary biology.[53] With the concept of ESS, Maynard Smith and Price translated the idea of the Nash equilibrium to the field of evolutionary biology and helped applications from game theory to enrich evolutionary thinking. Game theory is used in both fields to identify the interrelationships in conflict situations and to find solution. For instance, a classic conflict issue in evolutionary biology is the question of how more highly organised social forms can emerge when selection is only intended to benefit an individual.

Game theory is an aid which helps describe strategic thinking and allows it to be expressed as a mathematical formula. An abstract game serves to illustrate conflict situations and represent decision-making. There are always at least two players, rules of the game, and something to win or lose (the 'payoff'). The most famous game in this context is the 'prisoner's dilemma' (Fig. 8). The conflict between cooperation and self-interest is simulated in a hypothetical scenario.

Areas of application for game theory

Work based on game theory has already been recognised several times with the Nobel Prize in Economics; on the first occasion, by John C. Harsanyi, John F. Nash and Reinhard Selten in 1994. Game theory is frequently used in the field of evolutionary biology, for instance to study the dissemination and distribution of behavioural patterns in animal populations, the spread of infections, and cooperation mechanisms between individuals.

Evolutionary game theory can be applied to good effect in a biological context when the fitness (Tab. 1) of an individual depends on other individuals who have adopted an alternative strategy. Depending on variations in their genetic program, individuals in one species pursue different strategies in their struggle for resources or reproduction. In such circumstances, the payoff – or fitness – depends not only on the environment as a whole, but on the prevalence of other individuals with alternative strategies in the population. In the course of an evolutionary process, a stable equilibrium of the distribution of strategies develops, i.e. an evolutionarily stable strategy which can no longer be subverted by other, so-called mutant strategies.

A classic example is the 'hawk-dove conflict', where the descriptions 'hawk' and 'dove' merely symbolise an aggressive and a defensive strategy, and not literally two species of bird. If a hawk is competing with a dove for resources, the hawk will always win the resource, while the dove will fly off. Two doves will on average receive half of the booty each, while two hawks will on average suffer losses during the battle which exceed the value of the resource being fought over. It is clear that neither a population consisting entirely of doves nor one consisting en-

52 von Neumann & Morgenstern (1944).
53 Maynard Smith & Price (1973).

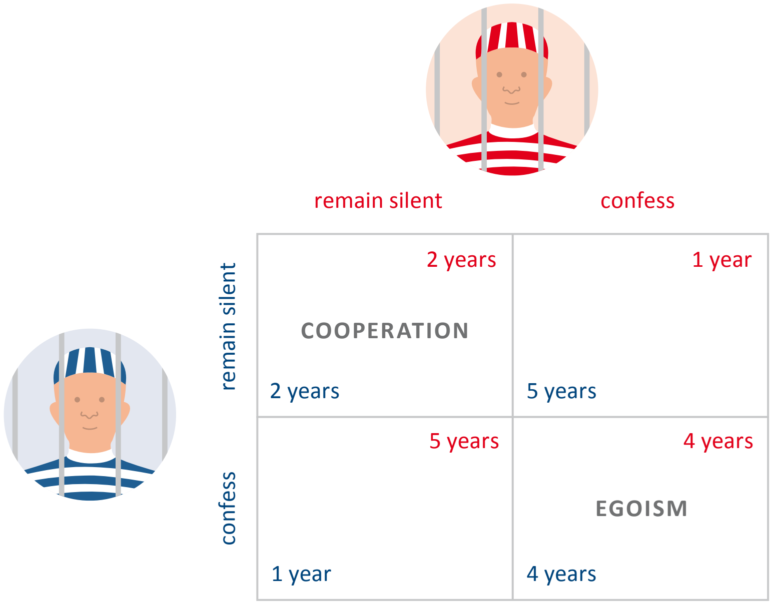


Fig. 8: Representation of the prisoner's dilemma principle. In this scenario, two prisoners are given a choice: if one of them confesses and incriminates the other, then the former will be sentenced to only one year in prison and the latter to five years. If both confess simultaneously, they will each be sentenced to four years. If neither confesses, then there is only sufficient evidence to sentence each to two years in prison. This gives rise to a classic conflict situation, in which each individual must choose between two options: to betray the other prisoner, or to keep silent. The optimal collective solution would be to cooperate with one another and both say nothing, as then each would only be sentenced to two years in prison. If both seek the maximum advantage for themselves as an individual, however, then they will both face four years' imprisonment. The principle of the prisoner's dilemma is representative of the general political problem of the over-utilisation of public resources which results from the conflict between one's own interests and those of one's community. The problem arises in a wide range of practical scenarios, from maintaining cleanliness in a communal kitchen to limiting the emission of greenhouse gases.

tirely of hawks can be in stable equilibrium. Among doves, the hawk strategy pays off, whilst among hawks, the dove strategy is beneficial. An evolutionarily stable system requires a mixture of hawk and dove strategies. The prevalence of the two strategies required to achieve an equilibrium can be calculated. A stable equilibrium is found in cases where the fitness of the player adopting the dove strategy is equal to that of the player adopting the hawk strategy.

Today, there are numerous applications of evolutionary game theory – not only in ethology, but also in microbiology, say. For example, certain yeast fungi produce the enzyme invertase, which breaks down fructose outside the cell and thus makes it available for uptake by the cell as a nutrient. Another phenotype, i.e. a cell with another genetic variant, forgoes the expensive production of the enzyme and behaves – as in the prisoner's dilemma – as a freeloader.[54] Equilibrium is achieved when there is an evolutionarily stable mixture of both strategies (ESS).

In the field of medical research, the application of game theory is bringing us completely new insights into cancer treatment.[55] Cancer cells emerge as independent clones.[56] They can be regarded as parasites within the body which develop their own evolutionary dynamism. Therefore, fighting them with chemotherapy must take into account the development of resistance, i.e. the dynamic production and spread of resistant cells. So in cancer treatment too, the challenge lies in solving

54 Archetti (2009).
55 Basanta et al. (2008), Gatenby (2009); cf. also Crespi & Summers (2005).
56 Nowell (1976).

a classic conflict issue. This subject is currently turning into one of the most active fields in which evolutionary theory and medical research collaborate.[57]

57 cf. e.g. the Cancer Evolution Collaborative Research Centre at Ludwig Maximilian University in Munich, Link: http://www.sfb1243.biologie.uni-muenchen.de/index.html (as per: 10.1.2017), and the 'Centre de Recherches Ecologiques et Evolutives sur le Cancer' in Montpellier (France), Link: https://www.creec.fr/fr/ (as per: 10.1.2017).

2. Evolutionary biology at schools and universities

Even people who keep themselves well-informed about the latest scientific findings often have considerable gaps in their knowledge about scientific procedures and lack confidence when it comes to evaluating scientific claims to validity. This is evident not least during public discussions about Darwin and what his findings mean to us, so that you hear statements such as, "Well, evolutionary theory is still just another theory."

A representative survey in 2009 by the Institut für Demoskopie Allensbach revealed that slightly more than half of the population were aware that humans had evolved from other life forms. When asked, "Do you believe that humas were created by God, or do you believe that humans evolved from other life forms?", 61 percent agreed with the second proposition (Fig. 9). Since 1970, when the question was asked for the first time (other life forms: 38 percent), this percentage has risen steadily.

Scientific theories are constantly being verified or falsified by reproducible experiments, and are potentially developed to the next stage or simply rejected. Often, the non-scientific public is unfamiliar with this modus operandi. But since questions relating to scientific theories and the general problems of instructing people about

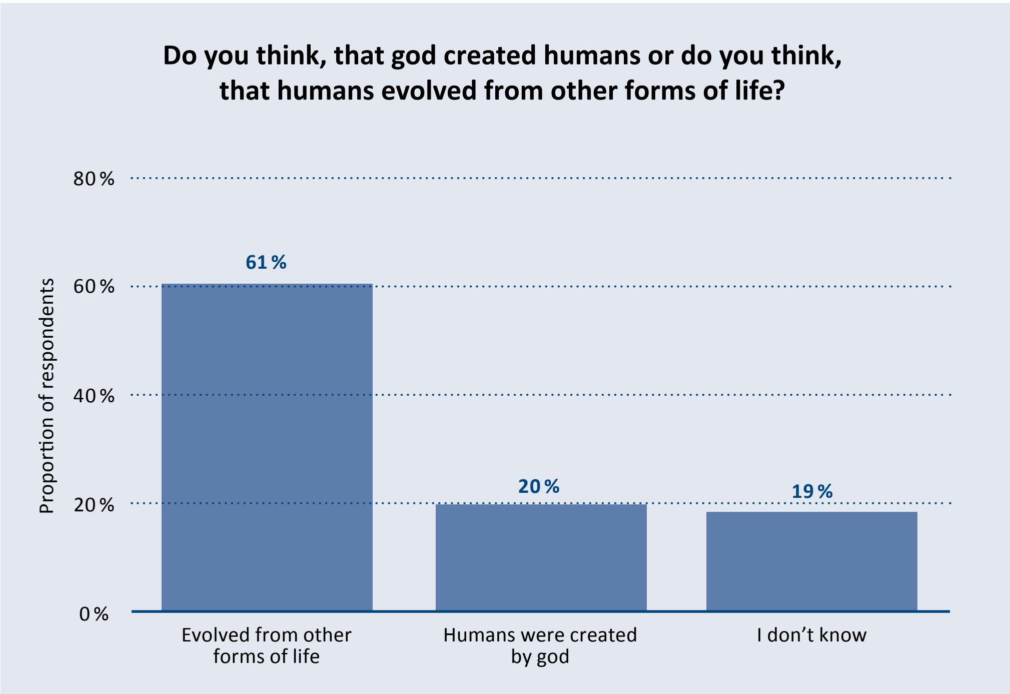


Fig. 9: A representative survey by Allensbach Institute for Public Opinion Research in 2009 revealed that for some 60 percent of those questioned, evolutionary theory explains the origins of humans. The fact that many people believe that man was 'created by God' is partly a result of the Bible stories they were taught in school. However, the major Christian churches no longer believe that the Bible makes dogmatic assertions about natural history. cf. http://www.ifd-allensbach.de/uploads/tx_reportsndocs/prd_0905.pdf (Rev.: 10.1.2017).

them exceed the thematic scope of this statement, they shall be addressed here only indirectly – namely to the extent to which a poor level of scientific education is responsible for certain gaps in knowledge about evolutionary biology.[58]

A strategy to improve education in evolutionary biology at schools and universities in Germany should be based on an analysis of the current situation which identifies the most important deficiencies and names their principal causes.

Such an analysis should encompass two aspects in particular: specific factors relating to the self-perception of humans requires them to understand a certain amount about their scientific make-up, and structural factors which impact upon the education of schoolchildren and students in the form of schools and universities.

The specific factors involved in developing a scientifically-based self-perception

The need for humans to understand a certain amount about their scientific make-up if they are to understand themselves is of particular relevance when it comes to causal models of evolutionary biology for the development of human characteristics. For then the more complex problems of applying evolutionary biology to phenomena of human existence are no longer obscured by the question of "whether humans really are descended from the apes".[59] Even the spread of creationism and theories of intelligent design does not appear to represent the main obstacle to the dissemination of knowledge about evolutionary biology in Germany, unlike in the United States. That said, experts are becoming increasingly concerned about its impact in the classroom.[60] Another problem area is of greater significance if one wishes to improve the standard of education in the field of evolutionary biology in Germany. The main obstacle (e.g. in the context of sociobiology, evolutionary psychology and evolutionary ethics) resides in the fact that an understanding of evolutionary biology puts into question basic attitudes which are deeply anchored in our common sense, and which are often based on two complementary mindsets.[61] On the one hand, evolutionary processes are regarded through the prism of life-world experiences, so that for instance a consciously planned design executed with a particular target in mind (modelled on the work of an engineer) is felt to be the only possible way of developing complex systems. On the other hand, an essential difference is claimed to exist between 'body and spirit' and 'nature and culture', making it appear pointless from the outset to seek scientific explanations for phenomena relating to the spiritual and cultural existence of humans.[62]

Evolutionary biology as a source of causal explanations for cognitive, social, and ethical aspects of human existence represents a broad and multi-layered area of subject-matter. However, we shall only be examining this in closer detail here to the extent that it provides insights into serious obstacles to the dissemination of evolutionary biology at schools and universities. A case in point is the difficulty of providing a scientifically-based representation of evolutionary mechanisms and processes, which places high demands

58 For additional information about the standard of scientific education in Germany, cf. the homepage of the IPN – Leibniz Institute for Science and Mathematics Education http://www.ipn.uni-kiel.de/de (as per: 10.1.2017) and the online portal of the MINT (Mathematics, Informatics, Natural Sciences and Technology) initiatives in Germany http://www.mintzukunftschaffen.de/ (as per: 10.1.2017).

59 Indeed, evolutionary biology currently plays an important role in this context by subjecting attempts to use concepts of race for the pseudoscientific classification of mankind to critical analysis; cf. Hossfeld (2011).

60 Graf & Lammers (2011). For a detailed discussion of creationism/intelligent design in Germany, cf. Neukamm (2009).

61 Such as for instance the Lamarckian use of explanatory models for cultural learning from experience in the case of the false prognosis of evolutionary adaptations; cf. Johannsen & Krüger (2005).

62 For an example of the self-perception of man as a freely-acting individual, cf. Voland (2007).

on the abstraction and visualisation skills of teachers and students.

Structural factors relating to institutional support for the teaching of evolutionary biology

Institutional organisation at schools and universities is central to the qualitative analysis of the status quo set out below. Despite the vast differences between individual schools and universities which result from the federalism of education policy in Germany, general statements can still be made about the institutional constraints on the teaching of evolutionary biology at German schools and universities.

2.1 Science education

The disparity between the scientific importance of evolutionary biology and its presence in academic life is based for a large part on the fact that there are too few researchers at German universities representing modern evolutionary biology. Although German biologists have played an important role in the acceptance and further development of Darwin's evolutionary biology since the days of Ernst Haeckel and August Weismann,[63] evolutionary biology in general and basic research into the theory of evolution in particular were neglected in Germany for generations after the period of the National Socialist dictatorship. For many years, the crucial advances made particularly in the development of the neutral theory of evolution, population genetics, the quantitative genetics of the phenotype, and game theory, had little influence on the appointment and creation of professorial chairs.

However, an increasing number of chairs have been established over the last fifteen years which focus on or are related to evolutionary biology. In the German research landscape too, evolutionary biology has been reinforced in a number of fields by the work of non-university research institutions (Tab. 3 and Fig. 10).

63 For an introduction, cf. Richards (2011).

Table 3: Specialists in evolution at universities and non-university institutions (alphabetically by location). These are locations at which several programmes of study and/or chairs and departments exist with links to evolutionary biology, and where it is clear that the subject is prioritised (as per: June 2016).

Location	Specialisation in evolutionary biology
Universities	
Free University of Berlin	· Six departments of evolutionary biology · MSc in Biodiversity, Evolution, and Ecology · Graduate programme in Biodiversity, Evolution and Ecology
Goethe University, Frankfurt (Main)	· Five departments focusing on evolutionary biology at the Institute of Ecology, Evolution and Diversity · English-language MSc in Ecology and Evolution
Christian Albrecht University, Kiel	· Seven departments in the fields of biology and medicine with a focus on evolutionary biology · English-language MSc in Molecular Biology and Evolution · Collaborative Research Centre (SFB) on the theme, 'Evolution of Meta-organisms' · International graduate school for evolutionary biology (International Max Planck Research School – IMPRS – for Evolutionary Biology – together with GEOMAR and the Max Planck Institute for Evolutionary Biology, Plön)
Ludwig Maximilians University, Munich	· English-language MSc in Evolution, Ecology and Systematics · International graduate school for Evolutionary Genomics, Ecology and Systematics · Collaborative Research Centre (SFB) on the theme, 'Evolution of Cancer Cells'
Westphalian Wilhelm University, Münster	· Five departments focusing on evolutionary biology at the Institute for Evolution and Biodiversity (IEB) · MSc Special Study Program in Evolution and Biocomplexity (specialism within the Masters course in Biosciences) · International graduate school, Münster – 'Evolutionary Processes in Adaptation and Disease'
University of Potsdam	· Five departments focusing on evolutionary biology · MSc in Ecology, Evolution and Nature Conservation · Cross-institutional university research focus on Functional Ecology and Evolution
Eberhard Karls University, Tübingen	· EVEREST graduate programme – 'Evolution and Ecology Research School Tübingen'
Max Planck Society	
Max Planck Institute for the Science of Human History, Jena	· Institute for research into the history of humanity with the focus on modern analytical methods · Departments of archaeogenetics, archaeology and the evolution of language and culture
Max Planck Institute for Evolutionary Anthropology, Leipzig	· Interdisciplinary institute for behavioural research and the study of the biological and cultural evolution of humans · Two out of five departments focus on issues related to evolutionary biology · International Max Planck Research School (IMPRS) 'The Leipzig School of Human Origins', together with the University of Leipzig
Max Planck Institute for Evolutionary Biology, Plön	· Basic research into evolutionary biology · All three departments focus on issues related to evolutionary biology · International Max Planck Research School (IMPRS) for Evolutionary Biology, together with the University of Kiel and GEOMAR
Max Planck Institute for Ornithology, Seewiesen	· Biobehavioural institute specialising in ornithology · Two out of four departments focus on issues related to evolutionary genetics and evolutionary ecology

Location	Specialising in evolutionary biology
Max Planck Institute for Developmental Biology and Friedrich Miescher Laboratory (FML), Tübingen	· Institute specialising in developmental biology and molecular genetics · Two out of six departments and three research groups at the FML specialise in issues relating to evolutionary biology
Leibniz Association	
Museum of Natural History, Berlin – Leibniz Institute for Evolution and Biodiversity Science	· Research museum with collection remit and public relations work · Interdisciplinary focus on the theme, 'Evolution and Geoprocesses' · Participation in the consortium, 'Berlin Centre for Genomics in Biodiversity Research'
Leibniz Institute for Zoo and Wildlife Research, Berlin	· Research institute set up to develop the scientific basis of species conservation · Three out of five departments focus on issues related to evolutionary biology · Participation in the consortium, 'Berlin Centre for Genomics in Biodiversity Research'
Alexander Koenig Zoological Research Museum, Bonn	· Research museum with collection remit and public relations work · Specialising in evolutionary biology, namely taxonomy and molecular biodiversity research
Senckenberg Society for Nature Research (Frankfurt, Dresden, Müncheberg, Wilhelmshaven, Görlitz)	· Research institutes and natural history museum with collection remit and public relations work · Specialising in evolutionary biology, namely taxonomy and systematics, evolution and biogeography, evolution and climate, adaptation and climate, the evolution of humans and their palaeoenvironmental conditions
Helmholtz Association	
GEOMAR, Helmholtz Centre for Ocean Research, Kiel	· Interdisciplinary institute for ocean research, specialising in marine ecology · Two out of five biological departments focus on evolutionary biology · International Max Planck Research School (IMPRS) for Evolutionary Biology, together with the University of Kiel and the Max Planck Institute for Evolutionary Biology

Last but not least, the Conference of Biological Sciences in Bioscientific Study Programmes ("Konferenz Biologischer Fachbereiche im Fachkanon Biologie")[64] has nominated evolutionary biology as an integral component of any biological Bachelor course in Germany. Similarly, the Conference of Ministers of Education (KMK) labels evolution as a mandatory element of the syllabus for all teacher training courses in the field of biology in its standard, whose title translates as *Common content requirements of the federal states for scientific disciplines and didactics in teacher training*.[65]

Nonetheless, the scope and depth of material on evolutionary biology taught at universities depends largely on how interested in the subject and how proactive the teaching personnel prove to be. Existing or planned (Master) courses which are explicitly based around the central concept of evolutionary biology (such as in Kiel, Munich, Münster and Potsdam – Tab. 3) are still few and far between, and/or insufficiently entrenched. If attempts are made to integrate evolutionary biology into the curriculum of courses other than those specialising in the subject, then this usually occurs thanks to the individual commitment of specific academics; they might organise lecture series or specialist seminars, for instance, or set up small study groups.

64 http://www.kbf.uni-halle.de/fachkanonbiologie.html (as per: 10.1.2017).

65 cf. KMK (2010), link: http://www.kmk.org/fileadmin/Dateien/veroeffentlichungen_beschluesse/2008/2008_10_16-Fachprofile-Lehrerbildung.pdf (as per: 10.1.2017).

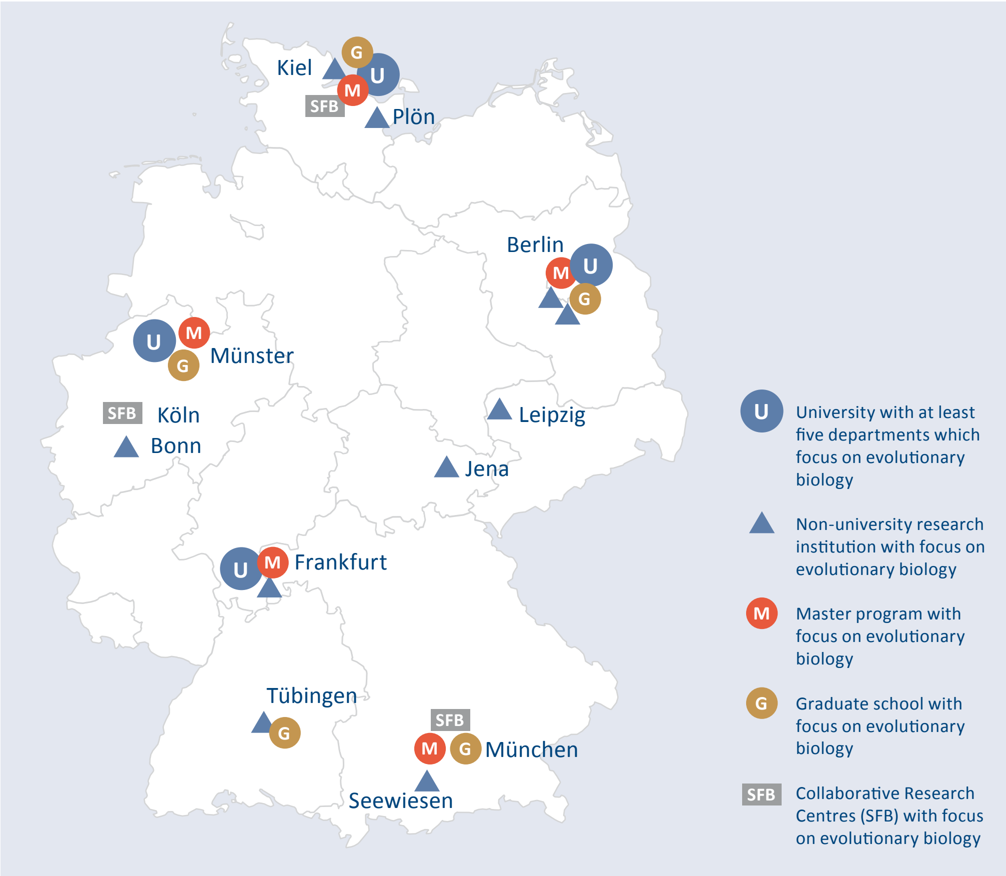


Fig. 10: A list of universities and research institutes in Germany with special research programmes on evolutionary biology. It is clear that some federal states and regions have a lot of catching up to do (Rev.: June 2016).

Despite the nature of the situation as concerns the teaching of evolutionary biology at German universities, which can generally be described as unsatisfactory, it has been possible to discern the first green shoots of improvement in recent years. There has been an increasing awareness in higher education circles that evolutionary biology constitutes the integrative framework of the life sciences.[66] This has led to a clear division in the German university landscape (Fig. 10):

- There are a few locations where there is clear evidence of specialisation in the subject through the establishment of chairs in evolutionary biology, and where the subject area is sufficiently integrated for it to be possible to apply for further third-party funding.
- However, these are outweighed by locations where evolutionary biology is taught as just one aspect of biology, without clear visibility, and where teacher training courses often use out-dated content.

This structural asymmetry is in stark contrast to the necessary breadth with which modern evolutionary biology should be taught, given the scientific and social significance which the subject clearly has. This matters particularly when it comes to the specialist training of future teaching personnel at universities.[67] Thus even

66 The importance should be mentioned here of the Volkswagen Foundation's funding initiative 'Evolutionary biology', including the partial initiative 'Evolutionary biology curriculum – a competition for innovative teaching concepts'; the support it has provided has been the driving force behind numerous projects – local in scale, perhaps, but nonetheless with a national impact; cf. Bild der Wissenschaft Plus (2009) and Hollricher (2009).

67 Findings from research into the teaching profession reveal a strong link between scientific knowledge and teacher training for student teachers in the field of biology; cf. Grossschedl et al. (2015); Kleickmann et al. (2014). A good grounding in evolutionary biology is an essential prerequisite for the development of specialist knowledge about how to teach the subject.

faculties which are unable to actually specialise in evolutionary biology should find ways of meeting the need for the subject to be taught. Otherwise there is a risk that the concentration of research into evolutionary biology at a few sites will impair the essential integrative impact of evolutionary biology in the scientific and educational training of student teachers, with the consequence that future biology teachers will then in turn be unable to teach the subject in class.

2.2 Teacher training

The methods used to train biology teachers are revealing themselves to be crucial to the dissemination of knowledge about evolutionary biology among schoolchildren, and thus in the longer term among the population as a whole. The education given to the biology teachers of the future is central to the dissemination of scientific research findings in schools. That is why improving scientific and teacher training in the area of evolutionary biology is effective on two different levels: it improves the status of the subject not only in schools, but also in higher education.[68]

The current situation regarding teacher training in higher education

The situation which exists in teacher training is a microcosm of that which is to be found in the teaching of evolutionary biology as a whole: although students show a great interest in the subject, here too the range of courses on offer is often dependent on the individual research interests of the teacher. Moreover, the students' poor grasp of evolutionary biology means that the training they are given in how to teach it very rapidly reaches its limits. In addition, teacher training courses at universities take their lead from the school curriculum which the respective federal state has set out for the teaching of biology. Content on evolutionary biology has been enshrined in the timetables for biology at lower and upper secondary level in nearly all federal states during the last ten years or so.[69] But the fact that the fundamental integrative nature of evolutionary biology is not reflected in biology classes constitutes another major deficiency in the curricula used throughout the entire secondary school system. Instead, it continues to be treated as just one of the many subject areas of biology. It is true that in the German equivalent of the sixth form of grammar school, the basic concepts of 'history and relatedness' and 'variability and adaptation' are a mandatory element of biology teaching across Germany, and are tested in the Abitur (university-entrance) examinations.[70] But to date there have been no empirically verified models to show how teaching these basic concepts can contribute to the building up of knowledge about evolutionary biology.

The current status of evolutionary biology in schools

The position occupied by evolutionary biology in teacher training is very strongly influenced by its de facto role in schools, and the changes introduced there. One positive development in 2004 was the inclusion in the intermediate school-leaving qualification of the basic concept of 'Evolution' in the educational standards of the KMK for the lower secondary level in the subject of biology. The obligation to focus on a grasp of biological principles should also be viewed in a positive light.[71] However, in many instances classroom educational standards are not implemented extensively enough. Furthermore, no substantial increase is apparent in the proportion of time allocated to evolutionary biology in the school syllabus, because there has been a simultaneous increase in

68 For an overview of teaching methodology in biology, cf. Gropengiesser et al. (2013).

69 KMK (2005).

70 KMK (2004).

71 cf. MNU (2006).

the wealth of material to be mastered from the fields of molecular biology, genetics and ecology. This ambivalence makes it difficult for teacher training to focus sufficiently on evolutionary biology, and gives student teachers a mixed message.

In terms of textbooks, the situation has improved with regard to the teaching of evolutionary biology in recent years. Yet there is still no textbook in use in Germany which does justice to evolutionary biology as an integrative framework for the teaching of the life sciences. This has led to a situation where much of the education provided to future teachers is based on teaching materials prepared locally rather than on school textbooks. But this has not given rise instead to the provision of long-term support for teacher training from institutions other than schools and universities. To date, for instance, there is a lack of any nationally coordinated, structured teacher training programme to evaluate the teaching of evolutionary biology in schools, despite the fact that valid proposals on curricular implementation have already been submitted by experts in the field of biology teaching.[72]

The role played by evolutionary biology in teacher training for subjects other than biology – in the humanities or social sciences, or in maths or physics, for instance – is practically non-existent. Special teaching events are, however, held sporadically within these subject areas. Such activities are heavily reliant on initiatives from outside the universities. One example was the Darwin Jubilee Year in 2009;[73] although it provided a stimulus for the organisation of many well-attended events and projects, only a very few of these bore fruit in the form of lasting endeavours to pick up in a class setting on the considerable interest in evolutionary biology.

72 cf. Harms et al. (2004), Kattmann (2003), etc.

73 The Darwin Jubilee Year in 2009 celebrated the 200th anniversary of Darwin's birth and the 150th anniversary of his work *On the origin of species*.

Proposals for the future development of university courses for future biology teachers

In recent years, educational experts have been stepping up their calls for evolutionary biology not just to be tackled in school as a special topic shortly before the Abitur exam; instead, it should be introduced explicitly as an independent subject area as early as from Year 5, and used as a structuring principle for the teaching of biology in general. In addition, children at primary school level should be familiarised with the concept through the inclusion of selected content in science classes.[74] It is only by taking such measures that the importance of evolutionary biology to both the educational and the scientific aspects of teacher training can be suitably reinforced in keeping with the central position it occupies in the life sciences. Schleswig-Holstein drew up an initial proposal in this respect in 2016 with its new subject requirements. This involved introducing evolution as a guiding principle for the teaching of biology at the beginning of secondary level at grammar schools, and recognising its role as an integrative framework right up to the Abitur.[75] Evolution would, accordingly, also be treated as a guiding principle when training student teachers how to teach biology during their eventual employment at grammar schools.[76]

If the importance of evolutionary biology for the life sciences as a whole is to be taken seriously, then it should be allocated a much larger share of the school curriculum than has been the case in the past.[77] A prerequisite for this is that future teachers of biology must be taught during

74 cf. for instance the Evokids initiative for the establishment of teaching content in evolutionary biology at primary school: http://evokids.de/sites/evo/files/evokids-resolution.pdf (as per: 10.1.2017).

75 To be found at: http://lehrplan.lernnetz.de/index.php?wahl=199 (as per: 10.1.2017).

76 The subject requirements for biology represent the mandatory basis upon which teaching material in the field of biology is to be developed in the schools of Schleswig-Holstein.

77 Dreesmann et al. (2011).

their course to use evolutionary biology explicitly as an integrative framework for biology lessons in class. Thus it is impossible to ignore the inadequacy of treating the basic principles and mechanisms of evolution only at the margins of various specialised classes during the scientific element of teacher training. Doing so makes it impossible for students to gain a consistent understanding of the process of evolution and the mechanisms underlying it.[78] Yet this is an essential prerequisite if they are to receive the appropriate teacher training. This places an obligation on teacher training courses to build on the students' sound specialist knowledge of biology and highlight proven obstacles to the learning of evolutionary biology among different age-groups.[79] At the same time, instructional strategies and teaching models must be conveyed which can be used specifically to teach evolutionary biology to school classes of different ages.[80] In this respect, scientific education for future biology teachers and advice on how to teach the subject must go hand in hand with one another in a coordinated fashion. At the same time, the guidelines for teaching biology in schools (curricula and syllabuses) must be harmonised with this process. University courses in the teaching of biology should also tackle creationism and the doctrine of intelligent design under the heading of evolutionary biology; this is essential if, rather than being neglected in schools, the subject area is instead to be dealt with professionally by biology teachers.[81]

78 For more about what biology teachers know about the difficulties of teaching evolutionary biology, cf. Dijk & Kattmann (2010); for more about the standard of knowledge of student teachers in Germany in the specialist areas of biology and biology teaching, cf. Grossschedl et al. (2015) and Grossschedl et al. (2014a), and for more on the connections between these, cf. Grossschedl et al. (2014b).

79 cf. Hammann & Asshoff (2014), Basel et al. (2013), etc.

80 cf. Zabel & Gropengiesser (2011), Rosengren et al. (2012), Neubrand & Harms (2016), Neubrand et al. (2016), Weiss et al. (2017), etc.

81 Kattmann (2000) offers suggestions on how to teach this subject.

3. Recommended action

The following recommendations are designed to breathe new life into the teaching of evolutionary biology at schools and universities and to elevate its contents to international standards. The proposals focus on changes to structure and content, i.e. on the organisation of university courses in science and teacher training and on the teaching of themes related to evolutionary biology in schools. The recommended action has been developed on the basis of an underlying strategy which is explained below.

Strategy, guiding principle and objectives

The status quo varies widely within Germany as far as the teaching of evolutionary biology at universities and schools is concerned, and the same is true of the associated target groups. This means that a coordinated approach is required to address the problems which exist at schools and universities. The guiding principle of this strategy is that coordinated improvements at schools and universities are mutually reinforcing: if there is more extensive teaching of evolutionary biology in schools, then this will make it easier for universities to tackle the subject in more depth. And if the teaching of evolutionary biology improves in universities, this will raise the standard of knowledge of student teachers about the subject and improve their teaching skills in it. If this outcome is to be achieved, curricula must be updated accordingly. Consequently, the recommendations contained in this statement are directed principally at universities, the KMK, the education ministries of the individual federal states, and institutions providing in-service teacher training.

The strategy proposed below aims to highlight specific areas for improvement in various institutional contexts. Consequently, it takes as its starting point the serious deficiencies which currently exist, as identified in the situation analysis, and provides recommendations on the measures to be taken in these specific areas. The deficiencies and recommendations described below are arranged in accordance with the following objectives, which should be pursued in parallel:

1. to survey comprehensively the current status of education in evolutionary biology and support positive trends,
2. to establish evolutionary biology in the curriculum and in teacher training as an integrative framework for the teaching of biology, and
3. to promote evolutionary biology as the basis of the life sciences and as a transdisciplinary research programme at universities.

3.1 To survey comprehensively the current status of education in evolutionary biology and support positive trends

The measures proposed below

1. draw on the teaching of evolutionary biology at schools and universities,
2. support the welcome changes we have seen in recent years, and thereby
3. improve the standard of knowledge about evolutionary biology in society, the political world and academia for the long term.

Deficiencies are identified and proposals made on how to improve the situation.

Deficiency 1: The disparity between the importance of evolutionary biology and the value placed on it in schools and universities

Recommendation 1: A detailed and quantitative stock-take should be undertaken of the situation as it applies to the teaching of evolutionary biology at German schools and universities.

The first stage should involve a comprehensive study of the disparity which exists between the scientific importance of evolutionary biology and its relevance in the classroom. A detailed and quantitative stock-take of the situation as it applies to the teaching of evolutionary biology at schools and universities is proposed, which goes beyond the brief qualitative analysis presented here. Such a survey should seek answers to the following questions:

- What teaching content on evolutionary biology is a mandatory examination subject for students of the life sciences and/or for student teachers?
- How much do school-leavers from the different educational backgrounds which form part of the German school system know about evolutionary biology?

The resulting data should help to consolidate and enhance existing positive trends, as well as to encourage the coordinated planning of new initiatives aimed at improving the teaching of evolutionary biology at schools and universities.[82]

82 Tools for recording the state of scientific and teaching knowledge with respect to evolutionary biology are provided, for instance, by the project, 'Measurement of professional skills used in teacher training courses for the subject areas of mathematics and natural science' (KiL; WGL; AZ: SAW-2011-IPN-2) conducted at the Leibniz Institute for Science and Mathematics Education.

Deficiency 2: The risk that existing positive trends will be undermined

Recommendation 2: A national coordinating group should be set up.

Coordinated support for individual projects designed to improve the status quo vis-à-vis the teaching of evolutionary biology at German schools and universities must not be made to wait until comprehensive empirical data has been gathered about the situation. Key players should be involved as quickly and directly as possible in improvement measures and receive backing for their proposals. 'Key players' are those specialist scientists, education experts and teaching staff who have made a decisive contribution to the positive approaches already adopted. This involvement and support might be effected through the setting up of a national coordinating group, which organises scientific and educational events to maintain the general interest in evolutionary biology at schools and universities in the long term, as well as consolidating the improvements which have already been introduced.

3.2 To establish evolutionary biology in the curriculum and in teacher training as an integrative framework for the teaching of biology

The quality of school lessons is of central importance when it comes to both the general dissemination of knowledge about evolutionary biology and recruiting the next generation of life scientists. That is why it is extremely important to strengthen the position of evolutionary biology in the classroom. Below are proposals for improving the biology and science syllabus as well as the teaching materials available.

Deficiency 3: A lack of overall planning within the curriculum for school lessons in evolutionary biology

Recommendation 3: A general curriculum entitled 'Evolutionary biology for all school types' should be developed which applies nationally and spans the year groups.

Structural changes to the teaching of evolutionary biology in schools should take content-related and methodological problems more seriously than in the past. An understanding of evolutionary timeframes and dynamic mechanisms calls for considerable visualisation skills on the part of both teaching staff and schoolchildren, and this requires special training. Moreover, only a few reliable studies have been carried out so far in the field of classroom research specific to evolutionary biology. So long-term planning is required before a sustainable restructuring of school lessons in the subject can be carried out. For this purpose, a national curriculum spanning all age-groups and suitable for all school types should be developed, which brings abstract/conceptual relationships together with clear examples and suggestions for experiments, as well as with other methods of teaching biology.

Such a curriculum should be drawn up jointly by specialist scientists, education experts and teaching staff with the aim of ensuring that the subject of evolution does not have to wait until the end of a student's school life before being introduced, but should instead run like a thread through all biology lessons from Year 5 on, as well as being integrated into other school subjects. Information which has already been taught should be revisited in greater depth and on a higher level as the student progresses through the school, and reflected on with a greater degree of sophistication. Topics from the field of evolutionary biology should have already been introduced at primary level. Not only should independent learning units on evolutionary biology be enshrined in the curriculum; care should also be taken to ensure that, as a matter of principle, as many subject areas of biology as possible are considered from the point of view of evolutionary biology. These measures should help ensure that crucial aspects of evolutionary biology are grasped in a systematic way – from reconstructing the history of life to understanding natural selection and recognising the dynamic relationships and connections to other disciplines, such as medicine and mathematics, which exist. In addition, teaching matter on evolutionary biology should go hand in hand in lessons with the application of the fundamental thinking and working methods used in biology. It is only in this way that schoolchildren will develop an understanding of the theories and facts fundamental to evolutionary biology.

A curriculum for the teaching of evolutionary biology should address the following core statements, which can be viewed as such by virtue of their relevance from the perspective of science, society and the individual schoolchild. The aim is both to provide the schoolchild with a scientific education, and to inform his or her actions in daily life:

1. **Without evolutionary biology, there is no scientific explanation for the diversity of life**

   Evolutionary biology forms the integrative framework of biological knowledge. Single-cell organisms – as well as more complex plants and animals, including humans – are subject to evolutionary mechanisms. When using examples in class, research findings from traditional biological disciplines such as palaeontology and comparative morphology should be produced as evidence, together with results from the fields of molecular biology and genome research.

2. **Without an understanding of evolution, there can be no profound understanding of biological complexity**

   Biological processes exhibit an unexpected complexity, even at molecular and cellular level, which can only be understood in relation to the underlying evolutionary context (e.g. the role of ribonucleic acids, RNAs, in protein synthesis, the complexity of signalling cascades, and the role of transmitters in nerve conduction). Thus consistent consideration of evolutionary principles is also essential in molecular and cell biology.

3. Without evolutionary biology, there is no understanding of the relationship between humans and their environment

From an ecological viewpoint, evolution is the source of all the diversity in current life forms, whose characteristics are constantly changing. Intraspecific diversity, together with species diversity and the variation in ecosystems (biodiversity) is a prerequisite for organisms to be able to adapt to changing environments. The consequences of domestication, agriculture, plant breeding and animal husbandry should be considered evolutionary factors in exactly the same way as applies to manmade changes to the earth, our global ecosystem. This forms the basis for the creation of sustainable social development.

4. Without evolutionary genetics, there is no deeper understanding of the role of chance and its laws in biological phenomena

Research into population genetics and neutral evolutionary theory are based on the mathematical analysis of random processes, allowing laws to be identified such as those familiar to us from physics (e.g. thermodynamics and diffusion processes); consequently, links can be established between their content. It is only within this context that we can understand natural selection, adaptation and the emergence of new species. This research also allows to categorise differences between populations and recognise the risks inherent in in-breeding.

5. Without game theory, we cannot understand the dynamics of social and economic interaction and cooperation

Game theory was developed in economics and evolutionary theory, and forms the basis for the analysis of conflict situations where there are competing interests. The 'prisoner's dilemma' (cf. Fig. 8) and the 'hawk-dove conflict' (Chapter 1.4.5) are now particularly widely-known. It is used to study the consequences of alternative strategies, which determine the evolution of patterns of behaviour and economic activity. Game theory is particularly important for an understanding of the evolution of cooperation mechanisms and the responsible treatment of shared resources (often described as public goods), which are defining features of our society.

6. Without evolutionary biology, there is no in-depth understanding of medical correlations

The history of human evolution is crucial to our understanding of both genetic and lifestyle diseases. Similarly, the interaction of the human organism with its microbial companions, i.e. the microbiome, can only be understood in an evolutionary context. Disruptions to these interactions must also be interpreted within this framework (consider, for instance, 'probiotic nutrition'). The way in which the adaptive immune system deals with infections and parasites, the consequences for the development of allergies, the evolutionary dynamism of the creation of cancer cells and the dynamic emergence of resistance to antibiotics by microorganisms are all excellent examples of ongoing active evolutionary processes which are of particular relevance to medicine. These topics are also being dealt with increasingly frequently in basic medical training under the heading of 'evolutionary medicine'. People must ultimately ask themself what medical progress signifies for their own evolution.

Preparing a curriculum which provides orientation, and in which these core statements can be prepared for school lessons in a structured way, might trigger the creation of innovative projects in schools. Current efforts by educational experts to ensure that evolutionary biology is introduced at primary level and taught at secondary schools as a common thread running through biology lessons would also be consistent with a curriculum of this kind. Corresponding developments should be accompanied by coordinated specialist research into the teaching of the subject.

Deficiency 4: The delay in implementing the latest scientific and educationally-relevant findings on evolutionary biology in schools

Recommendation 4a: Teaching materials other than conventional school textbooks should be prepared.

Improvements to the status of evolutionary biology in the classroom can only be achieved in the long term by restructuring teacher training, introducing changes to the curriculum, and publishing new school textbooks. About ten years would seem to be a realistic timescale. The attainment of these long-term goals should be tracked by the national coordinating group. But they should be preceded and flanked by short and medium-term activities. In order to be able to introduce the necessary changes with immediate effect, measures are proposed which might have a more rapid positive impact through the galvanisation of current student teachers and the improvement of in-service teacher training. In particular, this could include the preparation of teaching materials other than conventional school textbooks. Using such materials might enable educational models and concepts for the teaching of evolutionary biology to be implemented in a more flexible way, and allow for a quicker response to recent developments in the life sciences or in educational science. Such information can be disseminated more speedily via scientific journals and online portals than through textbooks, and individual target groups (students, student teachers, teaching staff and the leaders of study seminars) can be addressed directly. This would also form the basis upon which textbooks could be updated in the longer term.

Recommendation 4b: Extracurricular measures should be taken in the field of the life sciences to improve the teaching of evolutionary biology.

Alongside formal school lessons, extracurricular educational strategies (‘enrichment’) are becoming increasingly relevant both socially and in terms of education policy. Another way of counteracting the delay in improving the teaching of evolutionary biology in schools for subsequent generations would be to utilise learning opportunities which already exist outside the classroom to target the promotion of evolutionary science. Laboratories already established at universities and other institutions for the specific use of schoolchildren might be one option worth exploring, as might museums of natural history and natural history collections.

3.3 To promote evolutionary biology as the basis of the life sciences and as a transdisciplinary research programme at universities

Very close links exist in the German academic system between research and teaching. In-depth teaching of evolutionary biology which incorporates the latest findings will be found mainly at locations where research is also carried out. Reinforcing the fundamental role of evolutionary biology in teaching and research, and improving connectivity across disciplines and faculties, will also raise the standard of education available to students.

The life sciences are a leading discipline within science as a whole, and evolutionary biology is the overarching explanatory principle for the life sciences. The general validity of its ideas places evolutionary biology at the heart of integrative modern biology. This means that it is also relevant to many fields beyond the realm of evolutionary research per se, such as medicine, agriculture and fisheries, as well as behavioural and social sciences. In addition, theoretical evolutionary biology also bridges the gap with mathematics, physics and economics. To a large extent, modern experimental evolutionary biology also adopts genomic and bioinformatic approaches, which are now enumerated among the core competences of the life sciences. In the field of bioinformatics, evolutionary biology provides the basis upon which algorithms are prepared for data analysis. This is just one example of how evolutionary biology can contribute to interdisciplinary networking beyond traditional institutional or faculty boundaries. At some locations, such as in Kiel, Cologne and Munich, it is already performing this function to some extent. Thus, reinforcing the fundamental role of evolutionary biology in teaching and research can contribute to the long-term success of an entire university institution. Nonetheless, the subject has until now played only a secondary role at many German universities, meaning that its integrative potential has not been fully exploited.

Deficiency 5: A lack of breadth in the establishment of university research into evolutionary biology

Recommendation 5: Modern research and teaching methods should be applied nationwide.

Over the last ten years, a few universities have begun to specialise in this subject, partly as the result of an initiative on the part of the Volkswagen Foundation. They have demonstrated how combining the subject area of evolutionary biology with an approach based on molecular biology and mathematics can generate basic research worthy of international recognition. This development should be supported in the faculties by arguing the point that a transdisciplinary and integrative outcome can be achieved by adopting the perspective of evolutionary biology.

With the rolling out of the Excellence Initiative and increasing specialisation at universities – although more consolidation is required in this area – it is now time to attach particular importance to strategies aimed at expanding research and teaching in the field of evolutionary biology. Even if not every individual university needs to specialise in the subject, efforts should be made to ensure that evolutionary biology is represented at some level throughout the world of academia by making at least one relevant appointment at every university. Thanks to the additional specialisation we have seen in recent years, the next generation of qualified scientists is already standing by.

Deficiency 6: Insufficient use made of the potential of ideas arising from evolutionary biology as a factor in transdisciplinary integration

Recommendation 6: Transdisciplinary approaches should be encouraged.

The long-term growth of this field of research and study at universities should also reinforce our understanding of evolutionary biology as a subject which is particularly transdisciplinary in nature, being an independent, general branch of science which uses mathematical modelling. Those working in this field should therefore be seeking to collaborate with their counterparts not only in the life sciences, but also in medicine, physics, mathematics and economics. It is essential to remove the obstacles which exist in

Germany to the expansion of research and study in evolutionary biology as a transdisciplinary subject, not least in the light of the increasing importance of mathematical modelling techniques in systems biology and bioinformatics[83]. In the case of evolutionary biology, the spectrum of cooperation has a broad base. At one end of the range is classical multidisciplinary collaboration, such as that which exists between the fields of biology and medicine. At the other is evolutionary biology as a general transdisciplinary branch of science, in which research is conducted using experimental, mathematical methods as well as simulations, and which is not bound to any particular field of application. Such fields include, for instance, evolutionary economics, the theory of cultural development, evolutionary algorithmics and mathematical stochastics. Efforts should be made to establish suitable (Master) courses and graduate schools with close links to research specialisations and to welcome such innovations.

General scientific education, too, would be provided with a major new impetus by the consistent use of the integrative function of evolutionary biology to enhance our scientific understanding of the world, adding another layer to what we have already learned from the life sciences. Learning activities could be organised for students from widely varying branches of study; from the natural sciences via social and behavioural sciences to mathematics and information technology.[84]

83 Leopoldina (2014a).

84 Suitable lectures and seminars could be attended by Bachelor and Masters students either as compulsory or elective classes within modules which are part of general degree courses or interdisciplinary subjects.

Glossary

Allele
Variant of a particular gene

Anthropology
The study of humans

Biodiversity
Umbrella term for the diversity of ecosystems, biocenoses and species, as well as for the genetic diversity within a species

Creationism and intelligent design
From the Latin *creare*: to create; the dogma according to which the entire cosmos including all living organisms was at least for the most part created in its present form by a Creator God; cf. Graf & Lammers (2011). Adherents of intelligent design avoid religious arguments. They ascribe the creation of the world to an 'intelligent designer'.

Epigenetics
Molecular mechanisms which result in a greater or lesser expression of genes without changing the information stored in the primary DNA sequence

Evolutionary psychology
Branch of psychological research which attempts to explain human experience and behaviour through our knowledge of evolution

Fitness
Average number of descendants of an individual with a particular genotype in proportion to the number of descendants of another individual with a different genotype

Gene pool
The complete set of alleles present in a population

Gene scissors
Gene scissors (restriction endonucleases) were discovered as much as forty years ago. However, it was only after the development of new techniques, such as zinc-finger nucleases, TALENs (transcription activator-like effector nucleases) and CRISPR-Cas9 (clustered regularly interspaced short palindromic repeats – CRISPR-associated proteins), that it became possible to edit individual sections of the genome and remove or replace genes in a targeted way.

Genome
The complete set of genes present in a cell or organism

Genotype
Combination of parental alleles (set of two genes) which an organism has at a specific gene locus

Intelligent design
cf. 'Creationism and intelligent design'

Life sciences
Fields of research and courses dealing with the processes or structures of living organisms, or in which living organisms are involved. Apart from biology, this incorporates related fields such as biodiversity research, medicine, biomedicine, biochemistry, molecular biology, biophysics, bioinformatics, human biology, but also agricultural technology, nutritional science and food research.

Macroevolution
Evolutionary steps with great adaptive changes which go beyond changes in individual genes and their alleles (in contrast to 'microevolution')

Metabolome
The total number of metabolites present within an organism

Microbiome
All of the microorganisms which colonise the gut, skin, or other parts of the human body (in the case of the gut, often referred to incorrectly as the 'intestinal flora'). At least 1,400 species of bacteria inhabit the human

gut, where they form their own ecosystem (microbiota). Their species composition can vary widely, and is influenced among other things by diet, immune competence and medication, but also by the individual's genes.

Microevolution

Evolutionary changes to the prevalence of alleles within a population. This can occur as a result of adaptive or neutral mechanisms.

Molecular clock

Observation that the mutation rate among genes is often relatively constant. This means that molecular differences can be used to deduce the point at which life forms split from their common ancestor.

Morphology

Branch of biology which studies the structure and form of organisms

Mutation

During cell division, an exact copy of the DNA strand is created. An error in this replication is called a mutation.

Natural selection

The mechanism proposed by Darwin and Wallace to explain how organisms adapt to their environment and how they evolve

Palaeontology

The study of fossils of animal or plant origin (palaeozoology and palaeobotany respectively)

Pandemic

The large-scale outbreak of an infectious disease (across national and continental borders)

Phenotype

The characteristics and/or appearance of an organism. Can be caused by the genotype or environmental influences or both.

Plasticity

Ability of living organisms exposed to a variety of environmental influences to modify their morphological, physiological and ecological characteristics in such a way as to adapt to prevailing environmental conditions. For example, the growth habits of plants which are genetically identical can vary under different environmental conditions.

Population

A group of organisms of the same species which are capable of genetic exchange, and thus form a common gene pool

Population genetics

This studies the processes which influence the frequency of alleles (cf. microevolution).

Proteome

The entire complement of proteins coded by a cell or a living organism

Recombination

Genes are recombined during meiosis. Recombination allows new combinations of hereditary traits to occur in descendants in comparison with their parents.

Resistance

In contrast to acquired immunity, the inherent resistance of an organism to harmful external influences which can be the result of mutation, for instance. Resistance is based on a selection of better-adapted organisms or cells.

Stratigraphy

The study of the order and relative position of strata in geology

Systems biology

Branch of biology which attempts to improve our understanding of cell-biological processes and organisms as a whole, and to this end collates data on the regulatory processes of the genome, the proteome, the metabolome, etc.

Taxonomy

Science of classifying biological species based on the natural characteristics which connect them

Methodology

The motive for preparing this statement and the writing process

The preparation of this statement was inspired by the following members of the Leopoldina: Prof. Dr. Thomas Börner, Prof. Dr. Rudolf Hagemann, Prof. Dr. Ingo Hansmann, Prof. Dr. Widmar Tanner, Prof. Dr. Diethard Tautz and Prof. Dr. Ulrich Wobus.

In order to perform a qualitative appraisal of the existing status of evolutionary biology both as part of the school curriculum and in scientific disciplines and teacher training at universities, interviews were conducted in the summer of 2011 with experts in the science and teaching of evolutionary biology. Priority was given to institutions which have distinguished themselves in the teaching of evolutionary biology and in scientific education and teacher training by conducting their own projects, and which are consequently well-informed about the status enjoyed by evolutionary biology at German universities. The following key questions were asked during the interviews, giving the respondents an opportunity to paint an interdisciplinary picture of the role of evolutionary biology in the university education of scientists and teachers of the future:

- Status quo
  "Based on your personal experience and your contact with other universities, how would you describe the status of evolutionary biology as a subject offered to students of biology and other subjects, and to student teachers in the fields of biology and other subjects at German universities?"

- Trends in the very recent past
  "Are you aware of any significant changes in this situation in recent years (including as a result of the Darwin Jubilee Year)? Is there any difference in this respect between the teaching of science and teacher training?"

- Measures to be taken going forward
  "What options for improvement do you envisage? To what extent could the Leopoldina – as the National Academy of Sciences – play a facilitating role in this regard?"

A first draft of the statement was prepared in the autumn of 2011 based on the results of these surveys, with feedback provided by the Education Commission of the Society of Germany Naturalists and Physicians. The draft was discussed at subsequent sessions of the working group, and further improved upon by the spokesmen for the working group.

A version prepared in mid-2016 was appraised by national and international experts (see below), who had no previous involvement. Their recommendations informed the final version.

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Study guide database of the Association of Biology, Biosciences and Biomedicine in Germany (VBIO): http://www.studienfuehrer-bio.de/

Collection of Wikipedia links to individuals and concepts referred to in Tabs. 1 & 2. Most of the references are to English-language websites, as the German-language alternatives still often tend to use outdated concepts and terminology; proof – if proof were needed – of how important it is for the German-speaking world to make up lost ground in the field of modern evolutionary biology.

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Microbiome:
https://en.wikipedia.org/wiki/Microbiota
Sociocultural evolution:
https://en.wikipedia.org/wiki/Sociocultural_evolution#Neoevolutionism

List of abbreviations

AIDS:	Acquired Immune Deficiency Syndrome
CDC:	Centres for Disease Control and Prevention
CRISPR-Cas9:	Clustered regularly interspaced short palindromic repeats – CRISPR-associated proteins
DART:	German Antimicrobial Resistance Strategy
DNA:	Deoxyribonucleic acid
ECDC:	European Centre for Disease Prevention and Control, European health authority
ESS:	Evolutionarily stable strategy
EVEREST:	Evolution and Ecology Research School, Tübingen
FML:	Friedrich Miescher Laboratory
GDNÄ:	Society of German Naturalists and Physicians
iDiv:	German Centre for Integrative Biodiversity Research
IEB:	Institute for Evolution and Biodiversity of Westphalian Wilhelm University, Münster
IMPRS:	International Max Planck Research School; international graduate school for evolutionary biology
IPN:	Leibniz Institute for Science and Mathematics Education
KiL:	Measurement of professional skills used in teacher training courses for the subject areas of mathematics and the natural sciences
KMK:	Conference of Ministers of Education
Leopoldina:	Leopoldina National Academy of Sciences
MINT:	Mathematics, informatics, natural sciences and technology
MNU:	German association for the promotion of maths and science teaching
MSc:	Master of Science qualification
PLOS:	Public Library of Science
PNAS:	Proceedings of the National Academy of Sciences of the United States of America
RAS:	Renin-angiotensin system
REX consortium:	Resistance to Xenobiotics Consortium
RNA:	Ribonucleic acid
SFB:	Collaborative Research Centre
TALENs:	Transcription activator-like effector nucleases
VBIO:	Association of Biology, Biosciences and Biomedicine in Germany

Selected publications on science-based policy consultation

Tiefe Hirnstimulation in der Psychiatrie (2017)

Verbraucherpolitik für die Energiewende (2017)

Rohstoffe für die Energiewende (2017)

Zum Verhältnis von Medizin und Ökonomie im deutschen Gesundheitssystem (2016)

Wissenschaftliche und gesellschaftspolitische Bedeutung bevölkerungsweiter Längsschnittstudien (2016)

Mit Energieszenarien gut beraten – Anforderungen an wissenschaftliche Politikberatung (2015)

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Chancen und Grenzen des genome editing (2015)

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Public Health in Deutschland: Strukturen, Entwicklungen und globale Herausforderungen (2015)

Perspektiven der Quantentechnologien (2015)

Transplantationsmedizin und Organallokation in Deutschland: Probleme und Perspektiven (2015)

Die Energiewende europäisch integrieren – Neue Gestaltungsmöglichkeiten für die gemeinsame Energie- und Klimapolitik (2015)

Palliativversorgung in Deutschland – Perspektiven für Praxis und Forschung (2015)

Individualisierte Medizin – Voraussetzungen und Konsequenzen (2014)

Akademien fordern Konsequenzen aus der Ebolavirus-Epidemie (2014)

Frühkindliche Sozialisation – Biologische, psychologische, linguistische, soziologische und ökonomische Perspektiven (2014)

All of the above publications can be downloaded free of charge from the Academy's website as pdf documents.

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