Chapter 1

The present status of evolution education

by Ute Harms and Michael J Reiss

Abstract
Evolution is widely seen as the central, key, unifying framework of biology. Yet many school-aged students and adults understand relatively little of the theory of evolution, for a whole range of reasons ranging from the cognitive difficulty of some of the central concepts to rejection of certain key ideas, whether consciously or unconsciously. Prior to this volume there have been surprisingly few studies of research-based interventions that attempt to use existing knowledge to propose new pedagogies to try to teach evolution to learners more successfully, whether in schools or elsewhere. Successful learning here might be understood as cognitive gains about evolution, as acceptance of evolution or as an increased desire to continue to learn about it. In this chapter we review the existing field of evolution education, discussing the reasons why such understanding is limited, whether for cognitive, socio-cultural or affective reasons (Jones & Reiss, 2007; Rosengren et al., 2012; Kampourakis, 2014; Tracy, Hart & Martens, 2011; Newall, 2017).

Keywords: evolution education, science education research, biology education

Evolution – the core line of biology

Evolution through natural selection is a central, unifying and overarching theme in biology. Evolutionary theory is the integrative framework of modern biology and provides explanations for similarities and adaptive differences among organisms, biological diversity, and many features and processes of the physical world. It is also applied in numerous other fields, both biological (e.g., agriculture and medicine) and, increasingly, non-biological (e.g., economics and computer science), though its use in these other fields is contentious and is not considered further here.

The essential tenets of evolutionary theory have long been regarded as key parts of the foundations of science education (e.g., Bishop & Anderson, 1990; Beardsley, 2004; Nehm & Reilly, 2007; Speth et al., 2014). Accordingly, the American Association for the Advancement of Science (AAAS, 2006), the Next Generation Science Standards (NGSS, 2013), the National Education Standards of Germany (Secretariat of the Standing Conference of the Ministers of Education and Cultural Affairs of the Länder in the Federal Republic of Germany [KMK], 2005), the National Curriculum for England (DfE, 2014), as well as the official documentation of many other countries, all describe evolution as an organising principle for biological science and include the topic as a learning goal.

Although evolutionary processes may occur (and be applied) in numerous kinds of systems, unless specified otherwise, evolution generally refers to changes in populations or taxa of organisms due to the generation of variation and natural selection (Gregory, 2009). There is a massive empirical body of work on natural selection, myriads of processes involved have been elucidated, and extensive terminology has been developed (e.g., Rector et al., 2013). Nevertheless, biologists generally agree that three principles are necessary and sufficient for explaining evolutionary change by natural selection: (1) the generation of variation, (2) heritability of variation, and (3) differential survival and/or reproduction of individuals with differing heritable traits (e.g., Gregory, 2009). However, evolutionary change is still poorly understood by students throughout their time in education (Nehm & Reilly, 2007; Shtulman, 2006; Spindler & Doherty, 2009), science teachers (e.g., Nehm et al., 2009), and the general public (Evans et al., 2010). This poor understanding has been attributed to diverse cognitive, epistemological, religious, and emotional factors (for an overview see Rosengren et al., 2012) that evidently evolution education is generally not successfully coping with. Against this background, this chapter will provide an overview of the status of evolution education considering the three central aspects of education: (1) the students, (2) the teachers, and (3) the teaching (including the curriculum).

Students' understanding of evolution – what do we know?

For decades, scholars in biology education all over the world have investigated students' understandings of various evolutionary concepts (e.g., selection, adaptation). The result today is a substantial body of literature and knowledge of respective misconceptions. This knowledge is an invaluable treasure for further research on evolution education as it reveals obstacles that affect or specifically hinder students' learning of evolution and also elucidates links for fostering evolution understanding. Therefore, initially we will highlight the main findings on students' conceptions of evolution, addressing the main categories of misconceptions (according to Gregory (2009), complemented by Neubrand (2017)).

Selection and adaptation

Frequent misconceptions of students are apparent in Lamarckian, teleological (finalistic), and anthropomorphic explanations of the mechanism of evolution. In the Lamarckian understanding, features of an individual that it acquires during its lifetime are passed onto its offspring (Kampourakis, 2014). These conceptions are similar to the widespread teleological conceptions that describe changes as being goal- or purpose-oriented. New features develop because they are advantageous. The process is directed by a creator or by the organism itself and this process has a natural end rather than being permanently ongoing, as it is when evolution is understood scientifically. Thus, the significance of randomness and probability that trigger mutation and selection, respectively, are not fully appreciated.

Anthropomorphic conceptions can be seen as a particular version of teleological conceptions. Here also, evolutionary change is seen as being steered by the organism itself and, simultaneously, human characteristics are ascribed to the organism no matter whether it is a non-human animal, a plant, or a prokaryote. The way that evolution is described in textbooks, both in terms of the wording and formulations, often even supports the anthropomorphic way of explaining evolutionary processes (cf. Alters & Nelson, 2002; Bishop & Anderson, 1990; Nehm, Rector & Ha, 2010). The large number of studies (Table 1) that have elucidated such misconceptions show that the failure to appreciate the clear-cut distinction between the development of features that appeared by chance (e.g., mutation) and prevail because they fitted better to the environment than others (selection), on the one hand (scientific explanation), and a deliberate development of such features by the organism(s) themselves – because they serve a particular function better – on the other hand (misconception) severely hinders the understanding of evolution.

Another difficulty for understanding evolution is the distinction between the individual and the population level. The mechanism of selection affects the individual and its interdependency with the environment. Genetic variability leads to different phenotypes and the individuals of one population often show small differences in morphology, physiology, and behaviour from those in other populations of the same species. Often the significance of this kind of variation is not appreciated (Bishop & Anderson, 1990; Brumby, 1979, 1981, 1984; Evans et al., 2005; Gelman, 2004; Shtulman, 2006; Strevens, 2000). But the variability among the individuals in a population is one essential precondition for the process of natural selection. Without variation, the chances for survival and reproduction are the same (as far as natural selection is concerned) for all individuals. Genetic variation as the result of recombination and mutation leads, over the generations, to individuals in a population that are better adapted to the environment than others. Of course, evolution takes place at the population not the individual level (Kutschera, 2006). Only when considering a series of generations, can evolution be observed as changes in the frequency of variants (Campbell & Reece, 2006, p. 513). Very often, students do not realise the meaning of the population in this context. This leads to the misconception that adaptation occurs at the individual level (Brumby, 1979, 1981, 1984; Jimenez-Aleixandre & Fernández-Pérez, 1987).

Another resistant misconception is when learners regard adaptation as a final status or an event that, having started, then comes to an end (Baalman at al., 2005; Brumby, 1979, 1981, 1984; Ferarri & Chi, 1998; Sinatra et al., 2008). Such learners don't understand the process character of adaptation. This notion of the completion of adaptation is already implicit in teleological, anthropomorphic and essentialist conceptions. Whilst misconceptions about adaptation and selection in populations have been investigated thoroughly over the years, the origin of new taxonomic groups as the result of cumulative changes over huge periods of time, i.e. macroevolution, is less researched. However, so far as is known, the misconceptions about macroevolution primarily address the processes of speciation and aspects of phylogeny.

Speciation

The basic mechanism of macroevolution is the process of speciation. When reproductive barriers arise as a consequence of genetic divergence, new species emerge. Typically, speciation occurs from the accumulation of adaptation and selection processes over many generations (though certain events, e.g., chromosome mutations such as polyploidy, can cause such reproductive barriers to be set in motion very rapidly, even in a single generation). Thus, misconceptions about speciation can result from students' explanations about adaptation and selection. Additionally, creationist conceptions that ascribe speciation to a higher entity are important for significant numbers of students and in more countries than is sometimes realised (Reiss, 2011).

Phylogeny

One further obstacle to grasping the history of life is an adequate understanding of huge extents of time, i.e. some four billion years (Graf & Hamdorf, 2011, p. 32; McVaugh et al., 2011). Understanding this so-called 'deep time' comes up against the limitations of human imagination (Gould, 1992, p. 15). This is mirrored by misconceptions of students. They typically show severe problems in ordering evolutionary events in time (Catley & Novick, 2009; Trend, 2001). The comprehension of deep time affects the understanding of the cumulative development of living beings and consequently of the dynamic of the processes of adaptation (cf. van Dijk & Kattmann, 2010). Another aspect of the concept of phylogeny is the classification of species in taxonomic groups. Cladograms visualise family trees of organisms. Students tend to misinterpret these (Baum et al., 2005; Catley et al., 2013; Gregory, 2008; Meir et al., 2007; Novick & Catley, 2006; Novick et al., 2014; Phillips et al., 2012). In particular, they do not understand the meaning of the last common ancestor (Meikle & Scott, 2010). From this stems, for example, the widespread misconception that humans come from one of the species of apes that is found today.

Genetics, randomness and probability, dimensionality

The described patterns of explanation (Lamarckian, teleological, anthropomorphic) at the phenotype level also appear at the molecular level. Students not infrequently argue that genes become dominant because they are useful to the individual, that genetic information can intentionally be changed for the purpose of adaptation and that this change is carried over to the next generation (Baalmann et al., 2004; Brumby, 1979, 1981, 1984). Accordingly, students don't consider mutation and recombination as random processes (Fiedler et al., 2017; Johannsen & Krüger, 2005; Nehm & Schonfeld, 2007; Robson & Burns, 2011). Furthermore, they expect randomness and processes that rely on probability to be, in the main, inefficient and pointless (Garvin-Doxas & Klymkowsky, 2008).

To understand evolution requires consideration of concepts and principles at different levels of organisation (micro, meso, macro), and this has been shown to be very difficult for students (Ferrari & Chi, 1998; Niebert & Gropengießer, 2015). The processes that make up evolution take place over time periods from the order of seconds (or even more briefly) at the molecular level (e.g., mutation) up to millions of years, regarding the origin of new taxonomical groups at the level of species and above. To understand scales of time and space and be able to apply this knowledge to evolution appropriately are important preconditions for comprehending the theory of evolution, a comprehension that many students don't achieve.

Table 1: Overview on students' misconceptions of evolution (according to Gregory, 2009 and Neubrand, 2017)

Concept(s)	Misconception	Description
Selection and adaptation		
Inheritance	Lamarckian conceptions	Living beings change by active adaptation. These changes are passed on to their progeny.
	Andrews, Kalinowski & Leonard (2011); Baalmann, Frerichs, Weitzel, Gropengießer & Kattmann (2004); Bizzo (1994); Brumby (1979, 1981, 1984); Deadman & Kelly (1978); Demastes, Settlage & Good (1995); Ferrari & Chi (1998); Graf & Soran (2011); Kampourakis & Zogza (2008, 2009); Lammert (2012); Nehm et al. (2009); Nehm & Reilly (2007); Nehm & Schonfeld (2007, 2008); Prinou, Halkia & Skordoulis (2008); Settlage (1994)	
Intentionality	Teleological conceptions	Changes arise that are purpose- and goal-directed.

		Andrews et al. (2011); Baalmann et al. (2004); Beardsley (2004); Bishop & Anderson (1990); Brumby (1979, 1981, 1984); Deadman & Kelly (1978); Engel Clough & Wood-Robinson (1985); Evans, Szymanowski, Smith & Rosengren (2005); Flanagan & Roseman (2011); Greene (1990); Jensen & Finley (1995, 1996); Jimenez-Aleixandre (1992); Jimenez-Aleixandre & Fernández-Pérez (1987); Johannsen & Krüger (2005); Kampourakis & Zogza (2008, 2009); Kampourakis, Pavlidi, Papadopoulou & Palaiokrassa (2012); Lammert (2012); MacFadden et al. (2007); Nehm et al. (2009); Nehm & Reilly (2007); Nehm & Schonfeld (2007, 2008); Pedersen & Hallden (1994); Prinou et al. (2008); Settlage (1994); Sinatra, Brem & Evans (2008); Southerland, Abrams, Cummins & Anzlmo (2001); Tamir & Zohar (1991); van Dijk & Kattmann (2010); Weitzel & Gropengießer (2009)	
		Anthropomorphic conceptions	Transfer of human features to non-human animals and plants. Changes are the result of purposeful and goal-directed action provoked by maladaptation.
		Baalmann et al. (2004); Demastes et al. (1995); Engel Clough & Wood-Robinson (1985); Jimenez-Aleixandre & Fernández-Pérez (1987); Johannsen & Krüger (2005); Jungwirth (1975); Tamir & Zohar (1991)	
	Individual vs population	Essentialistic conceptions	The 'type', the commonalities of individuals, are crucial for evolutionary processes.
		Alters (2005); Andersson & Wallin (2006), Andrews et al. (2011); Bardapurkar (2008); Brumby (1979, 1981, 1984); Evans et al. (2005); Gelman (2004); Greene (1990); Halldén (1988); Jimenez-Aleixandre (1992); Shtulman (2006); Spindler & Doherty (2009); Strevens (2000)	
		Individualisation	Adaptation happens at the individual, not the population level.
		Brumby (1979, 1981, 1984); Halldén (1988); Jimenez-Aleixandre & Fernández-Pérez (1987)	
	Insularity	State/event instead of process	Adaptation is not a dynamic process.
		Baalman et al. (2004); Brumby (1979, 1981, 1984); Chi, Kristensen & Roscoe (2012); Ferarri & Chi (1998); Sinatra et al. (2008)	
Speciation		Spontaneous speciation	The origin of species is not a dynamic process.
		Evans (2000); Samarapungavan & Wiers (1997)	
		Creationism	All living beings have been created simultaneously and separately by God (creationism).
		Berti, Toneatti & Rosati (2010); Evans (2000); Großschedl, Konnemann & Basel (2014); Illner (2000)	
Phylogeny			
	Deep time		Deep time is not understood.
		Graf & Hamdorf (2011); van Dijk & Kattmann (2009)	
	Taxonomy		Relatedness and its representation do not depict the principle of the last common ancestor.

Baum, DeWitt & Donovan (2005); Catley, Phillips & Novick (2013); Gregory (2008); Meikle & Scott (2010); Meir, Perry, Herron & Kingsolver (2007); Novick & Catley (2006); Novick, Schreiber & Catley (2014); Phillips, Novick, Catley & Funk (2012)

Students' conceptions constitute the starting point for teaching. However, successful education first requires by teachers an adequate understanding of the relevant scientific concepts and information. Therefore, in the next section we discuss findings on (pre-service) teachers' knowledge of evolution and also their acceptance of the theory of evolution, as we know that knowledge and acceptance of evolution affect each other mutually. Sound subject matter knowledge generally comes with a high acceptance of evolution theory (Akyol et al., 2012; Athanasiou et al., 2012; Deniz et al., 2008; Ha et al., 2012), though some students with sound subject matter knowledge actively reject evolution theory, typically on religious grounds, and also with the willingness of teachers to integrate this topic extensively in their teaching (e.g., Großschedl et al., 2014; Nehm & Schonfeld, 2007).

Teachers' and pre-service teachers' knowledge and acceptance of evolution

There is empirical evidence that university students – even those majoring in science – have problems understanding evolution-related topics. They show comparable Lamarckian, teleological and anthropomorphic misconceptions to those shown by school students (e.g., Gregory, 2009). In a study with 552 high school biology teachers, Rutledge and Warden (2000) found only little knowledge of basic evolutionary concepts. Yates and Marek (2014) tested biology teachers in Oklahoma and showed that the lack of subject matter knowledge by the teachers was a reason for the development of students' misconceptions about evolution; they found that some students even showed poorer knowledge about evolution after the teaching than before. It became clear that the teachers' subject-related competence, independent of their personal university degree, was higher when evolution had played a central role in their study programme. Also, the particular biological content seems to trigger the difficulty to solve problems in evolution. Nehm and Ha (2011) and Opfer et al. (2012) showed that college students have fewer problems answering questions on the acquisition than on the loss of features during evolution (e.g., the evolution of webbed feet in ducks, and the loss of the ability to fly in the evolution of penguins, respectively).

The acceptance of the theory of evolution plays an important role for (pre-service) teachers' abilities to teach evolution. Rutledge and Warden (2000) describe acceptance of evolution as "perceptions of evolutionary theory's scientific validity, ability to explain phenomena, and acceptance within the scientific community" (pp. 13-14). Religious and epistemological beliefs, reflecting the capacity or willingness to consider opposing arguments, seem to affect the acceptance of evolution theory (Deniz et al., 2008). According to the Model of Conceptual Ecology (cf. Deniz et al., 2008), three factor categories can be distinguished: cognitive, affective, and contextual ones. For an overview on the literature concerning the factors influencing the acceptance of the theory of evolution, see Großschedl et al. (2014). The most important cognitive factors are the understanding of the theory itself (Akyol et al., 2012; Athanasiou & Papadopoulou, 2012, 2016; Deniz et al., 2008; Ha et al., 2012), the understanding of the Nature of Science (Athanasiou & Papadopoulou, 2012) and knowledge of genetics (Miller et al., 2006). The most relevant affective factors are religious beliefs and personal attitude towards science (Athanasiou & Papadopoulou, 2012; Graf & Soran, 2011; Losh & Nzekwe, 2011; Miller et al., 2006). In addition, gender and academic degree may predictive factors for the acceptance of evolutionary theory (Losh & Nzekwe, 2011).

Taking into account the findings from the empirical studies sketched here, it seems clear that to enable future and in service biology teachers to teach evolution wel, teacher education should address cognitive, affective and contextual aspects. However, how to do this is still frequently a question for science education research to elaborate.

Teaching evolution

One challenge for evolution teaching is its deceptive appearance: the central statements of the theory of evolution can be described in a few sentences and this can give a false impression that the theory is easy to understand. Only on closer examination does its complexity come to the fore. This contrast between superficial facility and masked difficulty can lead to an illusion of understanding (Monod, 1997, p. 390, cited in Graf and Hamdorf, 2011, p. 28) that is uncovered by the various misconceptions sketched above. These misconceptions are often very resistant against instruction (Beardsley, 2004; Ferrari & Chi, 1998; Gregory, 2009; Jensen & Finley, 1995; Kampourakis & Zogza, 2008; Nehm & Reilly, 2007; Spindler & Doherty, 2009). Thus, for teaching evolutionary concepts, educational approaches seem to be reasonable that consider noted misconceptions, making these explicit for students and offering tools to alter these towards a plausible conception (cf. 'conceptual change' according to Posner et al., 1982; 'model of educational reconstruction' according to Kattmann et al., 1997). Several authors recommend this procedure (e.g., Abraham et al., 2009; Grant, 2009; Kalinowski et al., 2010; Kattmann, 2005; Meikle & Scott, 2010; Robbins & Roy, 2007).

Besides this general approach to misconceptions in education, some authors recommend particular approaches for addressing misconceptions about evolution. These approaches include consideration of structural requirements as well as of content-related goal settings. It seems to be widely agreed that evolution education pictures the integrating character of evolution biology. In other words, evolution shouldn't be taught as a distinct topic – like cell biology or physiology can be – but as a/the core principle throughout biology education (Kattmann, 1995; Harms et al., 2004; Nehm et al., 2009; van Dijk & Kattmann, 2010). In this context, Kalinowski et al. (2010) stress the necessity to interrelate genetics and evolution (on higher levels) as a deeper understanding of genetics requires evolution knowledge and *vice versa*. The authors assume that in this way, many difficulties in teaching and learning evolution could be prevented. To teach evolution as a core principle throughout biology education in the course of schooling is dependent on structural regulations like school curricula. In many countries, evolution is described in the biology curriculum as one topic amongst many others. However, in Germany, currently some *Länder* (e.g., Schleswig-Holstein and Lower-Saxony) define evolution as a core principle throughout biology education at school secondary level. At the moment, it is still an open empirical question whether this approach will foster a better scientific understanding of evolution. Another aspect to be considered is when to begin evolution education in schooling. Campos and Sá-Pinto (2014) call for an early beginning. There is empirical evidence that even very young children (elementary level) are able to grasp correct conceptions about evolution (Catley, Lehrer & Reiser, 2005; Nadelson et al., 2009). However, in many countries evolution education doesn't start before middle or upper secondary level. Regarding time for teaching, the duration of time needed for learners to develop a correct understanding – especially when misconceptions already exist – is an open question (e.g., Beardsley, 2004; Demastes et al., 1995).

With respect to the content of evolution, many scholars stress the macro-evolutionary aspects in evolution teaching (Novick et al., 2014; Phillips et al., 2012; van Dijk & Kattmann, 2009), focus on random mechanisms like genetic drift (Beggrow & Nehm, 2012), and apply a relative time concept rather than teaching absolute time frames and exact dates (Trend, 2001; van Dijk & Kattmann, 2010). One focal point of recommendations addresses the concept of natural selection, a key concept that is fundamental for the understanding of evolution (Gregory, 2009). Several authors propose different key concepts that should structure evolution understanding. Mayr (1982) describes seven key concepts; Anderson et al. (2002) differentiate the theory of evolution into ten basic ideas, though more recent authors reduce these to three basic principles: variation, inheritance, and selection (McVaugh et al., 2011; Nehm et al., 2012; Nehm & Schonfeld, 2010; Tibell & Harms, 2017). Another perspective on evolution education arises from the discussion on so-called 'threshold concepts' (Meyer & Land, 2005). Meyer and Land (2006) proposed a further approach to explain the learning of complex concepts like natural selection and evolution that are abstract, rather than concrete in nature. They defined these threshold concepts metaphorically as portals that, once passed though by a learner, open up new, previously inaccessible, ways to develop knowledge.

Conceptual change theory and the threshold concept model jointly imply that knowledge of core abstract concepts, the 'thresholds', could be essential for the conceptual change required to gain conceptual knowledge of a particular content. In this respect, evolutionary theory can be regarded as resting on a conglomerate of several threshold concepts, including randomness, probability, temporal scales and spatial scales (Ross et al., 2010), that must be understood in order to understand evolution generally and natural selection specifically. For the learner, this opens up new ways of thinking that were not previously possible, and enables new extended understandings of subject matter. Whether evolution understanding will improve when considering these threshold concepts in teaching is still an open question (cf. Fiedler, Tröbst & Harms, 2017).

In summary, to characterise the present situation of evolution education there is surprisingly little empirical evidence on how to foster evolution understanding across the phases of education. We know that students, teachers and the public hold a wide range of resistant misconceptions on evolution but we have little knowledge on educational approaches that can successfully change this situation. To acquire such knowledge, intervention studies are needed that give evidence for educational methods and procedures that support a scientifically correct understanding of evolution.

The studies in this book

Against this background, this book presents a collection of studies that investigate a variety of tools to foster students' understanding of evolution. We begin with several studies undertaken in primary (elementary) classrooms. Such work is of particular significance given that some countries have now made evolution a part of the primary curriculum. First, Loredana Buchan, Momna Hejmadi and Laurence Hurst in Chapter 2 look at whether a four-lesson scheme of work (variation, natural selection, geological time lines and homology/common ancestry) can lead to increased understanding in primary and middle school students of all abilities. Then, in Chapter 3, Berry Billingsley, Manzoorul Abedin, Keith Chappell and Chris Hatcher examine pre-service teachers' perceptions of the advantages and disadvantages of a cross-curricular session in their course and also their attitudes to using cross-curricular teaching with their primary students. This cross-curricular session was designed in the light of the fact that evolution is widely seen by teachers and pre-service teachers as an area of science that is challenging to teach, with one of the reasons often given being a concern that the science may conflict with some children's religious beliefs. In Chapter 4, Terry Russell and Linda McGuigan review their research into the teaching and learning of evolution across the 5-14 age range. Their original focus was on the mandatory curricular requirements for 'Evolution and inheritance', newly introduced in England for ages 9-11. Closer engagement with teachers and primary students clarified the challenge and opportunity to take a broader, more universal, view of progression in this curricular domain. The need they perceived was to link disconnected fragments into a coherent experience of progression, reflecting the underpinning breadth, depth and interconnectedness of evolutionary theory.

Martin Scheuch, Jaqueline Scheibstock, Heidemarie Amon and Helene Bauer in Chapter 5 situate their work in the context of the Austrian school curriculum where evolution is only mentioned in grades 7 and 12. They therefore set out to develop a learning progression including grades 8, 9 and 10 to fill the gap and enable year-by-year learning of evolution. To assess the students´ learning within this learning progression, a longitudinal interview study was undertaken which revealed students´ conceptions of teleological thinking and goal-oriented adaptation. In Chapter 6, Jaimie Miller-Friedmann, Susan Sunbury and Philip Sadler assessed US middle and high school student understanding of national science standards – National Science Educational Standards (NSES) for middle school students and Next Generation Science Standards (NGSS) for high school students – for evolution with a nationally representative sample in diverse settings. They were particularly interested to determine whether students from a wide range of school types, socio-economic status and regions in the United States are being taught and are learning evolution equally.

Yi Kong, Nancy Pelaez, Trevor Anderson and Jeffrey Olimpo in Chapter 7 start from the established finding that a lack of tree-thinking abilities is a factor that hampers deep understanding of evolution. They therefore compared an innovative curriculum intended to develop tree-thinking abilities to that of a traditional tree-thinking curriculum with regard to how these curricula were implemented by Graduate Teaching Assistants in an introductory undergraduate biology classroom. In Chapter 8, Timothy Goodale reports on the effects on beginning science teachers in the USA of using instructional units involving the teaching and learning of genetics and evolution through context-based methods surrounding food security issues in Africa.

Alexandra Buck, Sofoklis Sotiriou and Franz Bogner in Chapter 9 look at the consequences of an inquiry-based, hands-on approach with multimedia workstations focusing on the *Archaeopteryx* fossil for understanding evolution. They argue that this approach is an example of shifting from STEM to STEAM (Science, Technology, Engineering, Arts and Mathematics) subjects. In Chapter 10, David Owens reports on the results of a gameful, inquiry-based learning intervention with the intention of enhancing motivation among undergraduates to learn in the context of plant evolutionary life history.

Briana Pobiner, William Watson, Paul Beardsley and Constance Bertka in Chapter 11 examine the impact of implementing constructivist, guided-inquiry 'mini-units' that focus on examples of natural selection in humans on advanced US high school students' understanding of key concepts and the frequency of cognitive biases and misconceptions. They also describe the effect of supplementing this instruction with lessons that help teachers negotiate student resistance to learning about evolution due to religious or cultural beliefs. In Chapter 12, Kathy Malone, Anita Schuchardt and Zakee Sabree start by noting that the use of models and modeling in science education has been demonstrated to achieve cognitive gains in several science disciplines. However, there is a dearth of quasi-experimental studies in secondary classrooms that examine *how* the use of models and modeling can affect the cognitive gains of learners in biology in general and evolution in particular. Accordingly, they report on a study of an evolution unit grounded in the use of modeling and its effects on learning in evolution and attitudes towards science in general.

In Chapter 13, Alma Gómez Galindo, Alejandra García Franco, Leonardo Gonzáles Galli and José Torres Frías point out that evolution education has not sufficiently explored the cultural and contextual aspects related to learning. They therefore discuss the possibility of teaching evolution using an intercultural dialogic approach in which they worked with indigenous students in the Mayan Highlands in Mexico, exploring their knowledge about domestication of maize and reflecting on how knowledge about domestication of maize could be relevant for learning evolution. Lisa Kenyon, Emily Walter and William Romine in Chapter 14 transformed a college introductory biology course to more practice-based learning environment, in which students constructed knowledge about evolution through explanation and argumentation, and examined the consequences for conceptual change around natural selection, mechanistic reasoning related to natural selection and engagement in argumentation around data.

In Chapter 15, Ute Harms and Daniela Fiedler report on two studies to test the hypothesis that one central problem of understanding evolution is comprehension of the abstract concepts of randomness and probability. In the first study, they analysed the relationships of students' understanding of randomness and probability with their understanding of evolution; in the second study, three interventions were applied to improve students' understandings of randomness: an animation, a text on randomness, and mathematical tasks. Jorge Groß, Kerstin Kremer and Julia Arnold in Chapter 16 present two case studies that research the interplay between creationist conceptions and evolution understanding in informal learning environments. Case study one deals with the topic of the emergence of humankind in an exhibition presented to visitors in an IKEA store; case study two deals with a guided tour about the evolution of life throughout geological eras in a natural history museum. In Chapter 17, Jo Nicholl and Paul Davies discuss the findings of a study in a small Natural History Museum to look at how the use of objects supports pre-service science teachers in both their subject knowledge and their pedagogic knowledge of biological evolution.

Finally, in Chapter 18, the two of us as editors present some overall conclusions for the various studies reported in this book and suggest future avenues for research depending on the characteristics of learners (e.g., age, religious affiliations) and the nature of the learning environment (e.g., in school versus out of school, mediated by teachers versus not mediated by teachers).

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