# Learning evolution through socioscientific issues

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CHAPTER 6

# Evolution education and outreach - important things to know about how to teach about evolution.

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## Abstract:

Although evolution is widely acknowledged as one of the most valuable scientific theories, it is also one of the most challenging subjects to communicate and teach effectively. This chapter provides a brief overview of some of the most significant topics relevant to effective teaching and communication about evolution. These topics include worldviews, the nature of science, the language of evolution, cognitive biases and misconceptions, reasoning about evolutionary phenomena, cases and curricula, pedagogical practices, and assessment and learning. Since the breadth of prior work is extensive, readers are encouraged to use this chapter as an entry point into the rich literature on evolution education.

**KEYWORDS**

*evolution, teaching, misconceptions, curriculum, pedagogy*

# INTRODUCTION

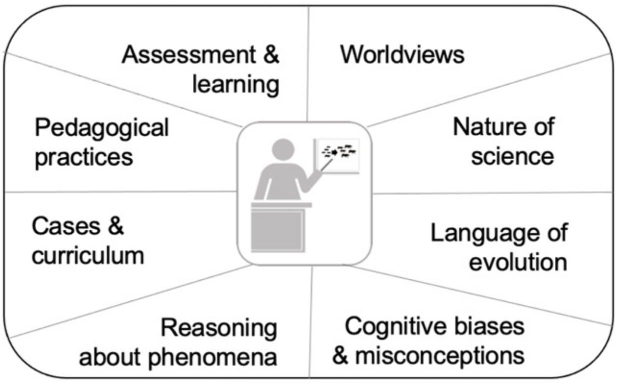
Although evolution is widely acknowledged as one of the most valuable scientific theories (Mayr, 1994; U.S. National Research Council, 2012), it is also one of the most challenging subjects to communicate and teach effectively. Hundreds of studies have documented a variety of sociocultural, linguistic, cognitive and epistemic factors that impact evolution understanding and acceptance (Figure 1).

Far fewer studies have integrated this expansive body of work or leveraged it to design interventions to help students and citizens overcome these obstacles and develop deep evolutionary understanding.

As such, addressing as many of the aforementioned factors as possible is likely to enhance outcomes. While much in evolution education remains to be known and accomplished, one unambiguous conclusion from prior research is that a robust understanding of human thinking and reasoning about the science of evolution—not just knowledge of evolution—is essential.

This chapter provides a brief introduction to some of the core challenges and solutions for teaching and communicating evolutionary ideas.

**Figure 1**
Major factors impacting effective evolution education and outreach (note: this figure is organised like a clock, with worldviews as the starting point).




# WORLDVIEWS

Globally, religion is inextricably interwoven with culture, identity, family and personal epistemology. Therefore, religion must be considered when teaching or communicating about evolution. This consideration does not necessarily have to involve conflict.

Although it is easy to perceive controversy when it comes to evolution and religion, we agree with the suggestion of Reiss (2019) that there is a more fruitful way to approach this relationship: to think of it as a sensitive rather than a controversial topic. Despite the lack of controversy among scientists about the facts of evolution, it makes many people feel uncomfortable because they perceive that it challenges their worldviews, with some even thinking of evolution as a nihilistic idea that deprives human life of deeper meaning.

Therefore, evolution should be approached as a sensitive topic. Such an approach requires respect for students' worldviews and a careful discussion about how evolution is not inherently atheistic or irreligious per se. There are numerous examples of people who have managed to accommodate both religion and evolution.

Notably, studies from the USA and beyond have found that approximately half of the scientific community adopts some form of religious affiliation (Ecklund et al., 2019). An effective way to engage with worldviews is to avoid conflict narratives and begin by presenting the evidence just cited about scientists and their religious affiliations. Once students realise that they do not have to feel threatened by evolution, they will be more likely to consider the science itself without worrying about its implications. This should be done to respect students' beliefs and to refrain from distracting them from the scientific concepts themselves. For some, evolutionary theory does have implications for worldviews. However, this is dependent on the inferences one draws from the theory, not the theory itself. Therefore, we suggest that such implications should be left out of any discussion until the scientific content is presented.

An analogy with morality may be useful for introducing the limits of science. Consider the termination of pregnancies for medical or other reasons. Science can tell us what happens in the fertilised zygote, in the implanted embryo and when the development of the nervous system begins.

But whether an embryo should be considered a human being or not, and whether it has rights, is not a decision that can be made on scientific grounds alone. Science generates facts about phenomena that occur at each of these developmental stages. Which of these we consider a rights-bearing living entity is a decision that can be informed by such facts but cannot be made based on them alone. Other philosophical considerations are also important.

Although moral decisions can be enriched by science in various ways, science cannot guide them because decisions about what is bad or wrong are made on a culturally/socially shared subjective basis. Overall, engaging with worldviews is an essential first step in evolution education and outreach because it can serve as an effective approach for reducing conflict and clarifying common misunderstandings (e.g., evolutionary biologists cannot be religious, or science answers all questions).

# NATURE AND PRACTICE OF SCIENCE

In public debates about evolution, if one looks closely at the arguments of anti-evolutionists, it becomes evident that much of the debate is not about evolution per se but about the nature of science itself: how science works, what kind of questions it can answer and how these answers are developed. For instance, a common argument against evolution is that it is *'just a theory'* (Miller, 2008).

This reflects a common confusion about the meaning of the word *'theory'* in everyday life and in science. In everyday language, the word *'theory'* refers to a hunch or speculation, whereas in science it refers to the most robust set of principles and models that scientists can use to arrive at explanations and predictions. Therefore, in such cases, anti-evolutionists must understand the structure and nature of scientific theories in general. Only once they do so might they be able to realise the many virtues of evolutionary theory (Kampourakis, 2020a).

Another example relates to the reasoning processes of scientists. Creationist Ken Ham argued in a debate with Bill Nye *'the Science Guy'* that the battle between evolution and creation is about interpretations of the same evidence. However, this is not accurate. In some cases, evolutionists and creationists do look at the same data and interpret them differently. However, their methods of doing so are strikingly different.

Creationists approach the data with predetermined conclusions (e.g., whatever religious documents suggest is true) and look for evidence to support these conclusions. When the data do not fit their conclusions, they find ways to make them fit or dismiss them altogether. This is not what scientists do. Instead, scientists do not have pre-determined conclusions. Although they may have hypotheses that they could test and should be open to rejecting or modifying them if they are not supported by the available data, scientists arrive at conclusions based on the evidence they have. In short, for scientists, it is the conclusion that must fit with the evidence, not the evidence that must fit with the conclusion (as is the case for creationists). Scientists are prepared to dismiss long-held theories if their growing understanding of nature reaches a point that these theories can no longer hold.

Another aspect of the nature of science relates to the explanatory practices of scientists. They are interested in explaining phenomena in the natural world, which is the realm of science. Whenever they fail to do so, anti-evolutionists often invoke quasi-scientific arguments involving God—a reasoning pattern that has been described as *'God in the gaps'.* However, the explanatory aims of scientists differ in an important way.

Scientists attempt to explain nature alone, which includes the entities and phenomena in the natural world, but not those outside it (i.e., the supernatural). Notably, science is a method of studying nature (known as methodological naturalism). Whilst this perspective does not deny the existence of the supernatural, it nevertheless recognises that one cannot study it. Consequently, there is no reason to use science to study it. Science is certainly concerned with the metaphysics of nature (i.e., the causes of natural phenomena). This stands in contrast to the view described as metaphysical naturalism, which is also known as philosophical or ontological naturalism.

These perspectives suggest that only natural entities exist, thus denying the existence of anything supernatural. This is the kind of argument that often confuses (and frustrates) anti-evolutionists; however, it is not an argument that most scientists make. The perspective that only natural entities exist is a view that characterises scientism, not science.

Scientism argues that the explanatory scope of science is not limited to the realm of the natural world and that science is the only way of knowing in general (see also Kampourakis, 2020a, Ch. 7).

In summary, addressing the nature of science is an essential early step in evolution education and outreach.

## THE LANGUAGE OF EVOLUTION

Language is the primary means through which scientific ideas have been communicated and transmitted throughout history (Rector et al., 2013). Like other scientific fields, evolutionary biology has a language of its own. Although some terms are unique (e.g., autapomorphy), many others are not and have scientific meanings that differ from everyday meanings (e.g., fitness, adaptation, mutation, theory).

For example, although biologists consider mutations to be randomly occurring genetic changes that can be neutral, beneficial or detrimental to an organism, in common use, the term mutation is often envisioned as a visible, harmful monstrosity at the phenotypic level. Moreover, fitness is often associated with physical health and strength as opposed to the number of offspring surviving and reproducing in the next generation.

Navigating the many meanings of terms like these makes effective communication challenging, particularly when multiple terms are used together in teaching or conversation. The situation is made much more challenging when teachers and scientists switch back and forth between *'everyday'* and scientific meanings (Betz et al., 2019). Assuming *'they know what I mean'* is a common mistake made by teachers. Simply put, language must be deployed carefully and addressed explicitly in evolution education and outreach.

Two general approaches may be used to address this challenge. First, learners can be introduced to evolutionary ideas and concepts using non-technical language that does not overlap with technical terms. This minimises interference with prior knowledge and definitions. Only after concept understanding is achieved is the scientific term attached to the concept.

For example, rather than introducing *'natural selection'*, teachers can explore many aspects of object sorting and the patterns that result from it (e.g., sorting objects with and without a blindfold, sorting for one feature but finding that another feature piggybacked along with it). Thus, one's understanding of different sorting processes and patterns can subsequently be tied to evolutionary terms and concepts (e.g., natural selection, genetic drift). A second approach lays out the linguistic challenges prior to any instruction or communication. In this approach, learners are explicitly informed of the dual meanings of evolutionary terms and how they differ in everyday and scientific contexts (Table 1).

Testing for the understanding of language mastery is crucial in any approach. Ambiguity *'alerts'* must also be made repeatedly during communication. In this regard, evolution educators have much to learn from foreign language teachers.

**Table 1**
Common and problematic terms that must be explicitly addressed prior to and during evolution education and outreach.

| Word | Everyday meanings that must be distinguished from scientific meanings |
|---|---|
| **Mutation** | Visible, harmful deformity or monstrosity at the phenotypic level. Must be contrasted with invisible variants that can be harmful, neutral or beneficial depending on various factors. |
| **Fitness** | Physical fitness, strength and outward phenotypic health. Must be contrasted with reproductive output (i.e., the number of individuals or genetic contribution to the next generation). |
| **Adapt/ adaptation** | Gradual acclimation or adjustment by an individual to a circumstance and the end point of a period of adjustment. Must be contrasted with population-level changes in the distribution of variation caused by natural selection. Emphasising what the environment can and cannot cause is also helpful here. |
| **Selection** | A conscious 'selector' making an intentional choice among entities. Must be contrasted with non-intentional sorting due to differential survival and/or reproduction (e.g., by abiotic conditions). |
| **Natural selection** | Multiple ideas (e.g., 'adapting to environmental change', 'survival of the fittest') that do not conform to the tripartite scientific theory (i.e., variation + heredity + differential survival/reproduction). |
| **Environmental pressure** | The 'force' that causes evolutionary change, including phenotypic and genetic differences. Must be contrasted with what the environment can and cannot cause (e.g., the environment cannot typically cause heritable mutations or new phenotypes). |
| **Evolutionary theories** | The guesses and speculations intrinsic to a field that cannot establish any 'facts' or know 'what really happened' (see also Nature and Practice of Science above). Must be contrasted with robust, tested and evidence-based explanations that have held up to intense scrutiny. |

The media and popular culture exacerbate this challenging situation. For example, individual cartoon characters and superheroes *'evolve'* and *'mutate'*, whilst viruses *'adapt to try to evade immune systems'*, representing everyday discourse that works against scientific understanding. The average person is bombarded with evolutionary language that is discordant with scientific meanings and scientific understanding.

There are at least two key elements that one should keep in mind when considering popular culture representations of evolution. The first element is that evolution is a process of change that occurs at the population level and not at the individual level. Individuals cannot evolve new features; instead, populations evolve because of the variation in the characteristics of their individuals and differential survival and/or reproduction through natural processes.

The second element is that this process of differential survival and/or reproduction is an unconscious, unintentional process that may lead to adaptation but also extinction. Understanding these two key elements is necessary for avoiding some common misunderstandings that often result, some of which are reviewed below.

# COGNITIVE BIASES AND MISCONCEPTIONS

Evolution is not simple or easy to understand, with claims to the contrary not being based on evidence. One must grasp many different fundamental biological concepts to be able to understand evolution. Evolution is also counterintuitive since it goes against our everyday intuitions about the natural world. Therefore, engaging with intuition is a necessary component of effective evolution education and outreach.

Consider the following example: ask anyone the simple question '*Why do birds have wings?'* The intuitive response most would give is *'To fly'.*

This is a rational and reasonable response because many common birds, such as pigeons, hawks and crows indeed use their wings to fly. However, if one thinks more carefully about this, examples of birds that do not use their wings for flight come to mind (e.g., swimming penguins and running ostriches). Therefore, the intuitive response, *'To fly'* to the question *'Why do birds have wings?'* does not work for all birds.

Now consider aeroplanes. When asked *'Why do aeroplanes have wings?'* all would answer *'In order to fly'.* What is different in this case? Since aeroplanes are artefacts designed by humans for the sole purpose of flight, their parts serve this exact purpose. Of course, there exist other aircraft that fly without wings, such as helicopters. However, when it comes to aeroplanes, there is no exception. 7

All aeroplanes have wings in order to fly because this is what they were designed for. This is not the case for birds, which have not been designed but are rather the products of natural evolutionary processes. This is a distinction that is not immediately apparent to many. Since we are surrounded by artefacts in our everyday life experiences from a very early age, we could become accustomed to intentional creation for necessary functions and the existence of parts to serve particular roles. Applying *'artefact thinking'* to organisms could be a result of this scenario.

Therefore, evolution education and outreach require attention to the distinctions between artefacts and organisms. Artefacts have fixed essences that relate to the purpose they are intended to serve, whilst organisms may have developmental essences that result in relatively consistent outcomes (e.g., the adult phenotype of each species); however, there is always variation that serves as the raw material for evolution. All parts of artefacts serve a specific role. In contrast, this is not the case for all parts of organisms. Moreover, those parts of organisms that do serve a function are the outcome of evolution by natural processes (not by design).

Thinking about the parts of organisms as if they were parts of artefacts is the result of particular cognitive biases or intuitions—spontaneous ways of thinking that in turn form obstacles to a scientific understanding of phenomena. Two very important biases are design teleology and psychological essentialism. These can be interpreted as stemming from our understanding of artefacts, which have fixed essences (essentialism) because they are designed to serve a purpose (design teleology).

These intuitions can lead to thinking about the features of organisms in the same manner (i.e., their unchanging parts are designed for a purpose).

These cognitive biases make the idea of evolution counterintuitive. Table 2 summarises cognitive biases that are relevant to teaching and communicating evolutionary ideas.

| Cognitive bias | Description and relevance to evolution |
|---|---|
| **Design-based reasoning** | An external agent (e.g., God, nature) guides the evolution of individual organisms towards a particular end so that they change to be able to survive. This idea is flawed because it assumes that an agent external to organisms themselves has designed them or their futures. |
| **Intentionality** | Individual organisms undergo modifications because they have particular intentions that have to be fulfilled. This is a flawed idea because the will of organisms or their wishful thinking (if they have any) cannot influence the course of their evolution. However, this does not mean that the intentions of organisms are irrelevant. Organisms have intentions (eat, mate, etc.) that are expressed in their behaviour, which might affect the course of their evolution—but not a specific, desired evolutionary end. |
| **Essentialism** | Individual organisms have fixed species essences and cannot undergo significant modifications, which makes evolution impossible. The problem here is that the robustness of development (e.g., a pig embryo will develop into a pig and not a dog) makes people think that there are essential species properties due to species essences that cannot change. However, even small changes in development can bring about large changes in adult forms, which can result in evolution. |
| **Need-based reasoning** | Individual organisms unconsciously undergo modifications to fulfil their needs in a particular environment and thus survive. This idea is flawed because any favourable traits emerge by chance and not because organisms need them. This is why the majority of species that have lived on Earth have gone extinct. |

**Table 2**
Cognitive biases to consider when teaching and communicating about evolution.

Misconceptions about evolution are also important (see Gregory, 2009 for a review). Whilst these may be due to the aforementioned cognitive biases, they may also be due to misunderstandings. In general, all the knowledge that we have takes the form of concepts, which are mental representations of the world. Scientific concepts, such as those related to evolution, are systematic representations of entities and phenomena that scientists use in their explanations and predictions. For any concept, it is natural for people to form different conceptions.

For example, although there is a dog concept, the conception of a dog that each one of us has may be different. When it comes to science, it is natural to form conceptions of phenomena and entities before we are taught about them since we encounter them in everyday life (consider a *'plant', 'animal', 'microbe,'* etc.).

These are described as preconceptions. When these are inaccurate, they are described as misconceptions. Ultimately, teaching aims to address these misconceptions and destabilise them for students to restructure them and adopt scientifically legitimate conceptions (Kampourakis & Nehm, 2014).

A requirement for this is that students are brought into conceptual conflict situations in which their conceptions are contrasted to the concepts and taught in a manner that helps them realise that the latter are more accurate than the former. Table 3 summarises some common misconceptions that must be explicitly addressed when engaging in evolution education and outreach. Pedagogical approaches for addressing these misconceptions are discussed in the section on pedagogy.

**Table 3**
Misconceptions commonly held by students and the general public. These are often combined with one another or with normative ideas to produce 'mixed' ideas (normative + non-normative).

| Misconception | Brief description of misconception |
|---|---|
| **Use or disuse of traits is a causal factor central to evolutionary change.** | The lack of utility of a trait is a direct cause of the decrease or loss of a trait over generations, or, conversely, the utility of a trait is the direct cause of an increase or addition of a trait. The use/disuse idea is often linked to the inheritance of acquired characteristics (see below). |
| **Traits acquired during a lifetime are inherited and passed on to the next generation.** | The character states of the traits of individuals, populations or species acquired during their lifetimes are commonly inherited and passed on to the next generation. This misconception interferes with the scientific concept of adaptation. |
| **Environmental pressures are a direct cause of difference, change and/or evolution.** | Environmental pressures (i.e., changes in the intensity or type of environmental condition) 'force' or directly cause living units (i.e., individuals, populations and species) to change their genetics and/or phenotypes. This idea is often a product of scientists using 'shortcut' language involving pressures causing changes. This idea is also linked to inappropriate teleology. |
| **Acclimation or simultaneous adjustment of all biotic units to change.** | Gradual adjustment by units (i.e., individuals, populations and species) to the environment is a pattern explained by the incorrect processes of trait use/disuse, acquired inheritance and/or environmental pressures (rather than by the differential sorting of heritable variants). |

# REASONING ABOUT EVOLUTIONARY PHENOMENA

The central aims of evolutionary biology include documenting patterns of evolution and building explanations for them. Documenting evolutionary patterns is complex and painstaking work that can take decades. Most students and citizens engage with evolution through the exploration of the following previously documented phenomena: patterns of change within a taxon (e.g., SARS-Co-V2 over a year), patterns of change in a larger lineage (e.g., non-avian dinosaurs and modern birds over millions of years) or patterns of change in phenotypic traits across many lineages (e.g., monogamy across mammal clades). Discussions often centre on what caused these patterns (e.g., Why did the new variants of SARS-Co-V2 documented by biologists start appearing?).

Therefore, our discussion of education and outreach focuses on thinking about previously documented evolutionary phenomena (e.g., patterns) rather than the scientific approaches used to generate them. Cognitive biases and misconceptions (see above) are not the only factors impacting reasoning about evolutionary phenomena.

Although the remarkable diversity of evolutionary phenomena is what gives evolution its widespread appeal, recent studies have shown that such diversity is a ‘double-edged sword’ when it comes to promoting evolutionary understanding (Nehm & Ha, 2011). Although many factors come into play when thinking about evolution (e.g., knowledge, cognitive biases, misconceptions, representational competencies), the types of ideas that are used to make sense of situations are not randomly evoked; instead, they depend quite heavily on the features of the cases in question (Figure 2).

Students tend to focus their attention on the unique, observable features of such cases and, as a result, knowledge retrieval from memory is driven by these features rather than by fundamental (often unobservable) causal principles (e.g., extensive heritable variation produced via mutation, differential reproductive success). In other words, the unique features of each example tend to eclipse thinking about general causal processes in living systems.

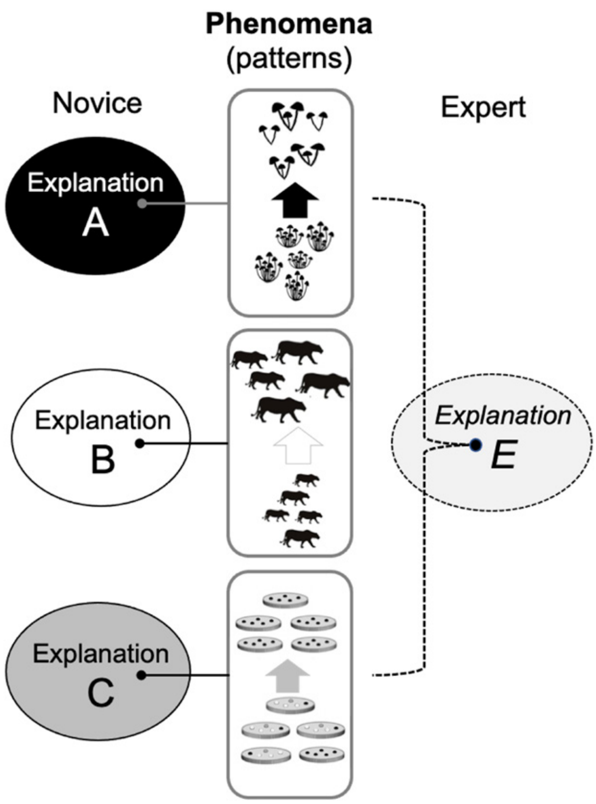
The result is that separate and unique explanations are constructed for each type of evolutionary example or phenomenon (Figure 2). For novices, the functional and ecological consequences of peppered moth colouration appear to have little in common with bacterial susceptibility to the drugs manufactured to kill them. Yet, both cases are explained in part by the differential survival of hereditary phenotypic variants produced by random genetic processes. Notably, understanding evolutionary phenomena requires the integration of causal and concrete elements.

One approach to addressing this challenge is to help students balance specificity, generality and causality when thinking about evolutionary phenomena or patterns. The first step in this approach (known as *‘cross-case comparison’)* involves creating pairs of evolutionary phenomena or patterns that differ in their concrete features (e.g., lactase persistence in humans vs. the loss of tusks in elephants; Darwin’s finches’ beak thicknesses vs. the loss of thorns in blueberry plants).

Rather than teaching cases sequentially or having students build explanations for a single case, students should work collaboratively to simultaneously identify the salient biological and causal similarities and differences between two cases (Nehm, 2014).

In general, learners have an easier time finding differences than similarities; thus, this step should come first. Many students will only *‘see’* superficial aspects of the cases (‘one is a plant and the other is an animal’, *‘one lives in location X and the* *other in location Y')* that often have little to do with causation and hence explanation. Pushing students to consider differences at a deeper level is often required.

**Figure 2**
Novice and expert reasoning about evolutionary phenomena.




Many superficial or concrete features of evolutionary problems (e.g., plant thorns, animal fur colour, lactase persistence, antibiotic resistance) activate different suites of conceptions and misconceptions during novice problem solving (Nehm, 2010; Nehm et al., 2012). A student may utilise misconceptions (e.g., evolutionary pressures cause mutations in response to the needs of the species) in one situation, and normative ideas in another (e.g., existing variation in a population was sorted and only some individuals survived). Sensitivity to evolutionary problem features is associated with idiosyncratic knowledge activation and the generation of multiple solutions to what experts consider the same problem (Nehm & Ridgway, 2011).

An important next step is to ask students to consider whether the features of the phenomena or patterns that they have identified relate to biological causes (e.g., *'Which of the differences that you have identified are of a causal nature?'*). This is not only an opportunity to discuss the nature of science in general but also to emphasise that causation is an essential feature of explanation. This is the point where students should begin to realise that there are few biological causes unique to a single phenomenon or pattern. Summaries of the differences—both superficial and deep, causal and noncausal—that student groups (or individual students) identify can be presented in a worksheet, group whiteboard or class chalkboard and discussed as a class.

Once the differences between cases have been identified and discussed, it is time to begin exploring similarities between the evolutionary phenomena or patterns. These similarities might encompass basic features (e.g., *'They have cells and use oxygen to metabolise food.'*) or more advanced ones (e.g., *'Heritable mutations constantly occur in both cases and can cause differences in the proteins that form parts of their phenotypes.'*). Guiding questions can also support thinking; for example, *'Do genetic differences among individuals relate to phenotypic differences in both cases?', 'Do endless resources and habitats characterise both cases?'*. Similarities across evolutionary phenomena or patterns should be summarised in parallel ways to the differences identified in the first part of the exercise.

Once the similarities and differences between the cases have been identified and discussed, the more challenging work of connecting process and pattern begins (e.g., the processes causing patterns of elephant tusklessness, or processes causing lactase persistence in humans).

This step will require scaffolding tools, such as lists of possible (normative and non-normative) ideas for students to discuss and evaluate as potentially relevant to both evolutionary situations. For example, since need-based explanations are commonly used by students (Table 2), they could evaluate the degree to which *'needs'* could explain the biological patterns in the two cases. Would the lack of food in a human population, as well as an associated need to consume and digest milk, impact the frequency of individuals with lactase persistence? How would this happen? Would poachers that differentially seek out elephants based on their phenotypes, as well as the elephants' need to lack tusks, cause individual elephants to lose them? A variety of causes could be evaluated as contributors to the patterns documented in the cases.

Scaffolding can also promote normative ideas (e.g., *'Do mutations occur in humans and elephants?', 'Do mutations contribute to phenotypic differences in humans and elephants?', 'How does that work?', 'Do phenotypic differences impact survival in humans and elephants under certain environmental conditions?').*

Cross-case comparisons must emphasise the similarity of process (e.g., mutation and genetic recombination generate large quantities of heritable variation; variation in genomes relates to variation in phenotypes; variation in phenotypes impacts competition for mates and securing resources) and dissimilarity of pattern (e.g., elephant tusk distribution, lactase persistence patterns). Evaluating potential causal contributors to different evolutionary scenarios focuses attention on how patterns might relate to processes.

The method of engaging students with multiple evolutionary phenomena or patterns and then gradually fading cognitive scaffolds (e.g., summary tables with similarities, differences and their causal natures) provides a test of preparation for future learning (i.e., '*Can students reason effectively about novel evolutionary patterns and phenomena?').* Using contrasting cases provides an opportunity for students to build abstract and causal models of evolutionary change that transcend specific cases.

This helps to address the well-documented fragmentation and context specificity of novice evolutionary reasoning (Nehm, 2018). This approach will help to counteract the largely unproductive approach in schools and outreach programmes of presenting interesting single cases (or in some cases, sequential ones) in detail.

Students and citizens must be prepared for making sense of future evolutionary phenomena or patterns.

# CASES AND CURRICULA

Employing interesting and relevant examples to illustrate evolution principles and practices is an important feature to consider when designing an evolution curriculum.

All too often, students learn about the same examples during their secondary and university education (e.g., Darwin's finches, peppered moths). The types of evolutionary examples are a central consideration because (i) students have difficulty reasoning across evolutionary examples and about novel evolutionary phenomena (see above), (ii) students often view evolution as personally unimportant, uninteresting or useless (Heddy & Sinatra, 2013) and (iii) the perceived utility of evolutionary topics is strongly associated with evolution acceptance (Borgerding & Kaya, 2022).

Recent work has explored what evolution topics students find interesting and reported that the evolution of HIV, avian flu and bacteria is viewed as more interesting than the evolution of humans (e.g., lactase persistence, high altitude adaptation) and other animals (e.g., elephants, fish, sheep; Jördens & Hammann 2019). Aligning the curriculum with student interest could increase students' motivation to learn about evolution.

The curriculum should also consider perceptions of the utility of evolutionary phenomena. Borgerding and Kaya (2022) studied the utility value of evolution learning topics and found that microevolutionary examples (e.g., disease transmission, genetic variation, antibiotic and pesticide resistance) were viewed as more useful than macroevolutionary examples (e.g., the relatedness of particular organisms and coevolution). Notably, maximising interest and usefulness is an important feature of curriculum design. Prior to discussing the specifics of the evolution curriculum, it is valuable to step back and consider how curriculum design should be envisioned in the first place.

Many countries have been working to shift their science curriculums away from focusing on large amounts of factual information and towards learning about fewer core ideas in greater depth (i.e., '*less is more'*).

In the United States, for example, the fundamental ideas that deserve the greatest focus are termed disciplinary core ideas (DCIs). DCIs are valuable because they help to make sense of a wide array of natural phenomena. However, effective engagement in the natural world requires much more than knowledge.

Students and citizens must understand the approaches, principles and frameworks that scientists use (along with DCIs) to make sense of natural phenomena (see also Nature of Science above). Such knowledge-building approaches (e.g., making observations, developing models, engaging in arguments about evidence and building explanations) are called 'science practices'. Science practices are the approaches that scientists across many disciplines have found to be essential for sense making. In addition to DCIs and science practices, scientists also make use of general ideas known as *'cross-cutting concepts'* (CCCs) to structure their work. For example, these include framing phenomena in terms of their pattern, structure-function, and cause and effect.

Three-dimensional learning (e.g., DCIs, science practices, CCCs) provides the tools for helping people make sense of and explain phenomena. Although the evolution curriculum should encompass all three aspects (Figure 3), this is often not the case.

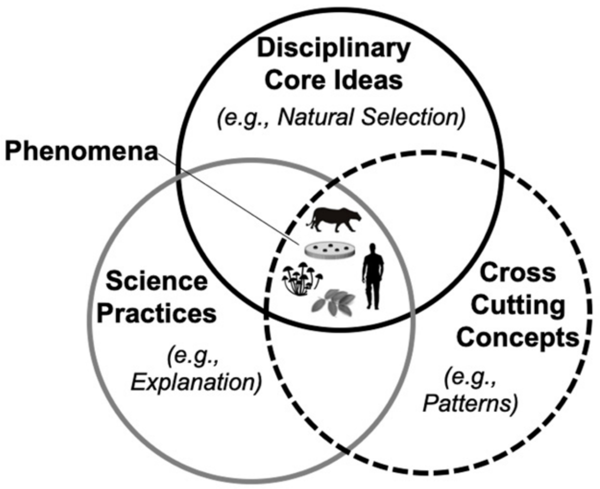
Unfortunately, there is considerably less research exploring how thinking about evolution intersects with science practices and CCCs. This raises the following questions: What do students think a meaningful evolution explanation should include? How do cognitive biases and misconceptions impact argumentation practices (and vice versa)?

Can students identify the salient features of an evolutionary pattern? To a large extent, the evolution curriculum in many countries has focused too heavily on the outputs of science (e.g., natural selection, phylogenies, extinction) at the expense of knowledge building competencies (e.g., how to approach explaining an evolutionary pattern, how to build a robust evolutionary explanation, how to establish a cause for an evolutionary pattern). Prior research suggests that fostering knowledge building competencies is a challenge.

For example, we know that students favour descriptions over causal explanations when engaging with evolutionary phenomena, that recognising the salient features of patterns when building explanations is a struggle and that argumentation too often lacks articulation with evidence.

A synthesis of prior findings in evolution education using a three-dimensional learning lens is needed alongside more curricula focused on teaching evolution using this approach.

**Figure 3**
DCIs, science practices, and CCCs. Three-dimensional learning, as exemplified by the US Next Generation Science Standards (NGSS), encompasses DCIs, science practices and CCCs. These three strands of science are used as an integrative framework for exploring phenomena in the natural world. In other words, these tools allow students to engage in science, not just learn about the outputs of science.




# PEDAGOGICAL PRACTICES

Active engagement in the learning process (e.g., collaborative learning, active learning) is a general pedagogical approach known to be effective for many science disciplines (Freeman et al., 2014). Interestingly, large-scale studies have raised questions about whether active learning by itself can promote evolutionary understanding (Andrews et al., 2011) and whether explicit attention to misconceptions in active learning settings is the essential element (Nehm et al., 2022). In addition to active learning and explicit attention to misconceptions, many other pedagogical approaches have been proposed (see Table 4). 7

Many of these approaches on their own have shown promise in small-scale studies. However, combinations including multiple strategies will likely generate the greatest impact. Despite the absence of robust, large-scale, evidence-based guidelines to inform pedagogical practices for teaching evolution, it is important to emphasise that understanding student thinking and reasoning about evolution is a prerequisite to any pedagogical implementation.

Many studies have shown that teachers are unable to identify limitations in students' evolutionary reasoning and often harbour misconceptions themselves (e.g., Hartelt et al., 2022).

**Table 4**
Pedagogical approaches for addressing misconceptions.

| Pedagogical approach | Description of how to address misconceptions |
|---|---|
| **Direct instruction** | Explicit discussion of misconceptions and why they are inaccurate in evolutionary contexts (e.g., Nehm et al., 2022). |
| **Cognitive conflict** | Present examples or situations that contradict expectations or cannot be explained by current mental models or misconceptions (e.g., Kampourakis, 2020b). |
| **Metacognitive strategies** | Introduce metacognitive opportunities for students to reflect upon, regulate and apply ideas across everyday and scientific situations (e.g., Gonzalez Galli et al., 2020). |
| **Metaknowledge discussions** | Foster the development of metaknowledge about types of explanations in biology and evolution (e.g., functional and mechanistic) (e.g., Trommler & Hammann, 2020). |
| **Historical examples** | Discuss how scientists previously struggled with the same concepts and illustrate how science helped to resolve confusing phenomena (e.g., trait loss) (e.g., Kampourakis & Nehm, 2014). |

# ASSESSMENT AND LEARNING

Having clear learning objectives and assessing them is of critical importance to effective teaching, with evolution education being no exception.

The first consideration when thinking about assessment is identifying what learners should know and be able to do with their knowledge after instruction is complete; in other words, education should always begin with the end in mind. Given that the curriculum should seek to foster growth in proficiency in the language of evolution, the nature of science and three-dimensional learning (DCIs, science practices and CCCs) across a variety of evolutionary case examples, what forms of assessment can be used to measure learning, and what pitfalls should be avoided?

Partly due to the rich information they generate about student thinking and reasoning, written explanations of evolutionary patterns have been used as an assessment approach for more than 30 years (e.g., Bishop & Anderson, 1990; see Ha & Nehm, 2014 for a review). Explaining patterns of change is also a realistic and authentic activity because most citizens will engage with patterns of biotic change at some point.

As new viruses evolve, new organisms are seen, new fossils are found, new taxa are named and new evolutionary phenomena are documented, people will try to make sense of these patterns (i.e., explain them). The COVID-19 pandemic is a case in point.

The general public's (and students') weak understanding of this phenomenon is reflected in common questions: Why did a new virus evolve? Why do new variants of the virus keep appearing? When will the virus stop changing? Of course, evolutionary change is the norm and it never stops occurring. Being introduced to Darwin's finches and peppered moths in secondary school has clearly not instilled abstract, generalised evolutionary understanding that extends beyond these cases.

One outcome of evolution education and outreach should be to prepare citizens for future learning. As such, it is as important to be able to make sense of future patterns as it is to make sense of those that one has been taught. The Assessment of Contextual Reasoning about Natural Selection (ACORNS) instrument (Nehm et al., 2012;

see ) was designed for this purpose. Specifically, the instrument was developed to help teachers and researchers understand thinking across a variety of scenarios, including different lineages (e.g., animals, plants, fungi), different trait polarities (e.g., loss vs. gain), different trait and taxon familiarities (porcupine vs. prosimian), different scales (within- vs. between-species) and different trait functions (e.g., colouration vs. locomotion).

Different types of patterns provide educators with information about how prepared learners will be when encountering new cases in the future. ACORNS results often show that students lack a robust model of evolution that generalises across phenomena.

This is a significant problem if we wish to prepare students for future discoveries and societal challenges. Other assessment formats (e.g., multiple choice) are more effective at determining whether students have mastered particular pieces of evolutionary theory. Explanation tasks assess the integration of understanding that reflects real-world applications.

Determining whether students have learned evolution is a remarkably complex process due to the factors discussed above. For example, if students lack a robust understanding of the nature of science (e.g., what questions science is best able to answer and those it is not), students may misunderstand what belongs in a science class and what types of knowledge are suitable for an explanation of evolutionary events (e.g., the origin of a new virus or disease). If students are confused about the

| Assessment target | At the end of evolution instruction, students should be able to… |
|---|---|
| **Nature of science** | …explain the boundaries or limits of science; refute common misconceptions about evolution and religion and the nature of science; illustrate how science practices are used to generate evidence-based understanding; differentiate everyday and scientific meanings of nature of science words and terms. |
| **Language of science** | …differentiate everyday and scientific meanings of evolutionary terms; use evolutionary terms accurately in scientific communication; identify ambiguous evolutionary language in a newspaper or online source and rewrite the news story to accurately reflect evolutionary concepts. |
| **Evolution knowledge (e.g., core ideas)** | …refute common misconceptions about evolutionary concepts and theories; explain how both random and non-random processes impact evolutionary phenomena; explain why environmental change is not necessary for natural selection; explain the role that mass extinctions play in the evolution of life on Earth. |
| **Science practices** | …build a single causal model lacking misconceptions that explains several novel evolutionary phenomena or patterns; construct a written scientific argument that integrates claims, evidence and reasoning about the sources of evidence most relevant to an explanation of an evolutionary pattern; develop a scientific explanation for a novel evolutionary phenomenon. |
| **Cross-cutting concepts** | …use a previously developed phylogeny to document patterns of character state changes in lineages; be able to identify cause and effect relationships in an evolutionary phenomenon. |

**Table 5**
Examples of possible assessment targets and associated learning objectives. Different assessment formats (e.g., true-false, multiple choice, open-ended writing, oral communication) can be used to measure proficiencies.

dual meanings of evolutionary terms, it will be difficult for them to understand what is being asked in an assessment question. If students are presented with a question about a single evolutionary scenario, it will be impossible to know whether they can use their knowledge to tackle another. If students are administered assessment tasks using different taxa, different types of traits or different polarities of change before and after instruction, it may not be possible to unambiguously isolate context effects from learning outcomes.

For these reasons, it is essential to assess a variety of targets (Table 5) and have items that are parallel in form and difficulty. In other words, all of the topics discussed in this chapter should be included in the gathering of evidence to determine whether communication and education have been effective.

# CONCLUSION

This chapter provided a brief overview of some of the most significant topics relevant to effectively teaching and communicating evolutionary ideas.

These topics include worldviews, the nature of science, the language of evolution, cognitive biases and misconceptions, reasoning about evolutionary phenomena, cases and curricula, pedagogical practices, and assessment and learning. Since the breadth of prior work is extensive, readers are encouraged to use this chapter as an entry point into the literature.

Focused attention on all of these topics is required for effective evolution education and outreach.

# REFERENCES

Andrews, T. M., Leonard, M. J., Cogrove, C. A., & Kalinowski, S. T. (2011). Active learning not associated with student learning in a random sample of college biology courses. *CBE—Life Sciences Education, 10*(), 329–435. DOI: 10.1187/cbe.11-07-00613

Betz, N., Leffers, J. S., Dahlgaard Thor, E. E., Fux, M., de Nesnera, K., Tanner, K. D., & Coley, J. D. (2019). Cognitive construal-consistent instructor language in the undergraduate biology classroom. CBE—*Life Sciences Education, 18*(4), 1–16.

Bishop, B. A., & Anderson, C. W. (1990). Student conceptions of natural selection and its role in evolution. *J Res Sci Teach, 27*(5), 415–427.

Borgerding, L. A., & Kaya, F. (2022). Is knowledge of evolution useful? A mixed methods examination of college biology students' views. *International Journal of Science Education, 44*(2), 271–296. DOI: 10.1080/09500693.2021.2024913.

Ecklund, E. H., Johnson, D. R., Vaidyanathan, B., Matthews, K. R., Lewis, S. W., Thomson Jr, R. A., & Di, D. (2019). *Secularity and science: What scientists around the world really think about religion.* Oxford University Press.

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *PNAS, 111*(23), 8410–8415. DOI: 10.1073/pnas.1319030111

González Galli, L., Peréz, G., & Gómez Galindo, A. A. (2020). The self-regulation of teleological thinking in natural selection learning. *Evolution: Education and Outreach, 13*(6).1-16

Gregory, T. R. (2009). Understanding natural selection: Essential concepts and common misconceptions. *Evolution: Education and Outreach, 2*, 156–175.

Ha, M., & Nehm, R. H. (2014). Darwin's difficulties and students' struggles with trait loss: Cognitive-historical parallelisms in evolutionary explanation. *Science & Education, 23*(5), 1051–1074. DOI 10.1007/s11191-013-9626-1.

Hartelt, T., Martens, H., & Minkley, N. (2022). Teachers' ability to diagnose and deal with alternative student conceptions of evolution. *Science Education, 106*(3), 706–738.

Heddy, B.C., & Sinatra, G.M. (2013). Transforming misconceptions: Using transformative experience to promote positive affect and conceptual change in students learning about biological evolution. *Science Education, 97*(5), 723–744.

Jördens, J., & Hammann, M. (2019). Driven by topics: High school students' interest in evolutionary biology. *Research in Science Education, 51*(1), 599–616

Kampourakis, K. (2020b). Students' "teleological misconceptions" in evolution education: Why the underlying design stance, not teleology per se, is the problem. *Evolution: Education and Outreach, 13*(1),1-12

Kampourakis, K. (2020a). *Understanding evolution.* Cambridge University Press.

Kampourakis, K., & Nehm, R. H. (2014). History and philosophy of science and the teaching of evolution: Students' conceptions and explanations. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 377–399). Springer.

Lennox, J. G., & Kampourakis, K. (2013). Biological teleology: The need for history. In K. Kampourakis (Ed.), *The philosophy of biology: A companion for educators* (pp. 421–454). Springer.

Matthews, M. R. (Ed.). (2014). *International handbook of research in history, philosophy and science teaching* (Vols. 1–3). Springer.

Mayr, E. (1994). *What evolution is.* Basic Books.

Miller, K. R. (2008). *Only a theory: Evolution and the battle for America's soul.* Penguin.

National Research Council (2012). *Thinking evolutionarily.* The National Academies Press.

Nehm, R. H. (2010). Understanding undergraduates' problem-solving processes. *Journal of Biology and Microbiology Education, 1*(2), 119–121.

Nehm, R. H. (2018). Chapter 14: Evolution. In M. Reiss & K. Kampourakis (Eds.), *Teaching biology in schools* (pp. 1-14). Routledge.

Nehm, R. H., & Kampourakis, K. (2014). History and philosophy of science and the teaching of macroevolution. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 401–421). Springer.

Nehm, R. H., & Ha, M. (2011). Item feature effects in evolution assessment. *Journal of Research in Science Teaching,* 48(3), 237–256.

Nehm, R. H., & Ridgway, J. (2011). What do experts and novices "see" in evolutionary problems? *Evolution: Education and Outreach, 4*(4), 666–679.

Nehm, R. H., Finch, S., & Sbeglia, G. (2022). Is active learning enough? The contributions of misconception focused instruction and active learning dosage on student learning of evolution. *BioScience*.

Nehm, R. H., Beggrow, E. P., Opfer, J. E., & Ha, M. (2012). Reasoning about natural selection: Diagnosing contextual competency using the ACORNS instrument. *The American Biology Teacher*, 74(2), 92–98.

Rector, M. A., Nehm, R. H., & Pearl, D. (2013). Learning the language of evolution: Lexical ambiguity and word meaning in student explanations. *Research in Science Education, 43*(3), 1107–1133.

Reiss, M. J. (2019). Evolution education: Treating evolution as a sensitive rather than a controversial issue. *Ethics and Education, 14*(3), 351–366.

Trommler, F., & Hammann, M. (2020). The relationship between biological function and teleology: Implications for biology education. *Evolution: Education and Outreach, 13*(11), 1-16.