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THE AMERICAN BIOLOGY TEACHER

Theme Issue: Darwin and Evolution

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About Our Cover

Battle of the Saurophaganax and Seismosaurus

The scene of two huge dinosaurs—one looking for dinner and the other fighting for its life—is found in the New Mexico Museum of Natural History and Science in Albuquerque. This is a fitting cover for our annual issue on evolution because, of course, these animals are often evoked in discussions of change through time. There was considerable evolutionary change that produced the diversity within the dinosaur group (approximately 300 genera and 700 species). One dinosaurian lineage—the two-legged theropods—evolved to become modern birds, a point that should always be mentioned with some awe whenever chicken is on the menu.

Not only should we consider evolution when discussing the dinosaurs but also we can learn much about the nature of science with these animals. For instance, we continue to refine our understanding of the final days of the dinosaurs. We now know that the end of the dinosaur era was about 65 million years ago, a date recently pushed back from 64 million. The names of dinosaurs also change as paleontologists consider the fossil evidence and examine the growth trajectories of these animals. With the announcement of a new species, it is not uncommon for scientists to question if that animal is just a juvenile or more complete fossil of some dinosaur already described. We all must understand that conclusions in science are tentative and that we come closer to the truth with more evidence, consideration, expertise, and collegial argument.

Appropriately, bones of both creatures in this photograph have been found in New Mexico. The tyrannosaur-like *Saurophaganax* sp. ("king of the reptile eaters") was one of the largest meat-eating dinosaurs of the late Jurassic period (approximately 150 million years ago) and is known from the famous Morrison Formation and elsewhere. It is shown attacking the plant-eating *Seismosaurus* sp., fossils of which were discovered in 1979 in the Ojito Wilderness Area, northwest of Albuquerque, New Mexico, but it is also known from Oklahoma. There is still debate about the validity of this name, but it is likely that this creature was just a particularly large example (110 feet long) of the well-known *Diplodocus*. This is a good example of the self-correcting aspect of how science works even though the reclassification of dinosaurs undoubtedly frustrates paleontologists and elementary school children alike.

This digital image was recorded with a Nikon D810 camera using an image-stabilized 28-300mm zoom lens. The photographer is William F. McComas, editor of *The American Biology Teacher*, Parks Family Professor of Science Education, and director of the Project to Advance Science Education at the University of Arkansas (mccomas@uark.edu).

Contents

Feature Article

Research on Learning

Inquiry & Investigation

Tips, Tricks & Techniques

Departments

THE AMERICAN BIOLOGY TEACHER

Guidelines for Authors

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Guest Commentary

Glenn Branch and Ann Reid

Laying the Foundation: How Is Evolution Taught in Middle School?

When John Freshwater, who taught eighth-grade science in Mount Vernon, Ohio, was fired in 2011, it was in part because he was presenting to his students what he described as evidence *for and against* evolution—which was, in fact, creationist propaganda. In doing so, he flouted not only the Establishment Clause of the First Amendment to the Constitution but also the directives of his district administration and the guidance of professional organizations such as the National Association of Biology Teachers (NABT). The NABT rightly describes evolution as "a necessary part of teaching biology" that "should be a major theme throughout the life science curriculum," while rejecting calls for creationism to be presented as part of the science curriculum.

It would be comforting to think that the Mount Vernon situation was a rare aberration—especially because middle school science teachers play a huge, though often unappreciated, role in evolution education. Although typically presented most thoroughly in high school biology classes, evolution usually appears first in middle school life and earth science classes, where it serves as a vital foundation for future learning. Natural selection, adaptation, and evolution itself are mentioned, and multiple lines of evidence for evolution are introduced, at the middle school level in the Next Generation Science Standards (NGSS) and in the state science standards of a majority of states. But what are middle school science teachers in fact teaching about the status of evolution? Are middle schools inundated by Freshwaters?

Fortunately, no. According to a new study published in *Evolution: Education and Outreach*, based on a national representative survey of public school science teachers conducted by researchers at the National Center for Science Education (NCSE) and Penn State University, a solid majority—82%—of middle school science teachers who teach evolution agreed that they emphasize the scientific consensus on evolution, a figure reassuringly comparable to the 86% of high school biology teachers who do the same. Yet the middle school science teachers were substantially less likely than their high school counterparts to conform to NABT's recommendation of emphasizing the scientific consensus on evolution while not presenting creationism as a scientifically credible alternative, as shown in Figure 1.

The disparity is plausibly in part due to a lack of knowledge about the scientific consensus on evolution, for understanding that there is a well-founded and evidence-based scientific consensus on evolution is a prerequisite to presenting it accurately and confidently. The survey asked, "To the best of your knowledge, what proportion of scientists think that humans and other living things have evolved over time?" The actual proportion, according to a 2014 survey of members of the American Association for the Advancement of Science, is 98%. But only 55% of middle school science teachers responding to the survey selected the correct range of 81–100%, as opposed to 71% of high school biology teachers.

That lack of knowledge in turn is likely to reflect middle school science teachers' lack of knowledge about evolution in general. Of course, some are highly knowledgeable, such as Bertha Vazquez, a middle school teacher in Miami who directs the Teacher Institute for Evolutionary Science, a project aimed at equipping middle and elementary teachers to present evolution effectively. Her efforts to promote middle school evolution education won her NABT's Evolution Education Award in 2017. But teachers like Vazquez are in the minority at the middle school level. Indeed, in the survey, 42% of middle school science teachers reported having no preservice or in-service coursework covering evolution whatsoever, as compared to only 19% of high school biology teachers.

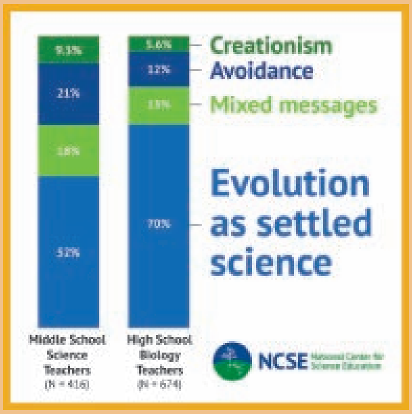

Figure 1. Reported emphasis when devoting one or more class hours to teaching either evolution or creationism. After Table 8B in Glenn Branch, Ann Reid, and Eric Pluitzer, "Teaching Evolution in U.S. Public Middle Schools: Results of the First National Survey," *Evolution: Education and Outreach* 14, no. 8 (2021).

Improvements in middle school evolution education are on the horizon, thanks to improvements in the treatment of evolution in state science standards. A previous study by the NCSE / Penn State team found that the adoption of the NGSS was significantly associated with a shift between 2007 and 2019 among high school biology teachers toward conforming to NABT's recommendation of emphasizing the scientific consensus on evolution without presenting creationism as a scientifically credible alternative. And while earlier data on middle school science teachers are not available, the new study also found that in 2019, middle school science teachers in states that have adopted the NGSS were significantly more likely to conform to NABT's recommendation.

Yet improvements in the treatment of evolution in state science standards are not enough. To realize the potential for improvement in evolution education in the middle school science classroom, these teachers must receive the support they need to teach evolution effectively. That includes appropriate preservice and in-service coursework, both in evolution and in effective evolution pedagogy; instructional material that reflect the scientific consensus on evolution in engaging and effective ways; and the support of their colleagues and their professional organizations. For it is just as true in middle school as it is in high school that nothing in biology makes sense except in the light of evolution.

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FEATURE ARTICLE

Of Newts and Neurotoxins: Coevolution in a Predator-Prey System Provides a Multifaceted Backdrop for Engaging Students

MATTHEW R. FISHER

Abstract

Storytelling can stimulate learning by delivering scientific content within a narrative that increases comprehension and engagement. In this article I describe the coevolutionary arms race between toxic newts and predatory garter snakes. This engaging story centers on the use of a deadly neurotoxin called tetrodotoxin (TTX) as an antipredator defense. Some species of newts contain TTX in their tissues, but resistance to TTX has developed through convergent evolution in garter snakes and other species. TTX resistance results from mutated voltage-gated sodium channels. These channels, whether TTX resistant or not, are found in all animals and are vital to the function of nervous and muscle tissues. Through reciprocal selection, coevolution has created phenotypic matching between toxic newts and TTX-resistant garter snakes across their range in the western United States. In other words, as newts became more poisonous, garter snakes became more resistant. These results and the scientific process behind them are discussed in detail. This story can be used by educators to provide a unifying and engaging backdrop as students learn multiple aspects of biology, such as protein structure, genetics, phylogenetics, electrical signaling, evolution, and the process of science.

Key Words: *coevolution; tetrodotoxin; newt; garter snake; mutation; genetics; resistance; voltage-gated sodium channel; neurotoxin.*

The enigma of TTX production remains to be solved, perhaps by one of your students!

○ Introduction

Your thoughts race as you swallow the first bite. Is your mouth going numb or is your mind playing tricks on you? You know that numbness precedes paralysis and that paralysis precedes death. You wonder why you took this unnecessary risk.

You are eating fugu, a Japanese delicacy made from pufferfish. It is purportedly delicious but also potentially deadly (McCurry, 2016). As you savor the fugu's texture and umami taste, you trust that the chef expertly prepared the dish without tainting the meat with the puffer's poison, a paralyzing compound known as tetrodotoxin (TTX). This toxin is found in a diverse group of species, from bacteria to pufferfish to newts, and it disables the nervous and muscular systems of vertebrates, even at low doses. Some TTX-producing species, such as the rough-skinned newt, can contain enough toxin to kill 50 full grown humans (Yasumoto & Yotsu-Yamashita, 1996). Why would newts have such ridiculously high amounts of toxin if only a little will do?

Enter the humble garter snake. To them, newts are like fugu: a savory meal that could kill from TTX poisoning. But certain species of garter snakes eat with impunity, gobbling up entire newts and living to tell the tale. How do they achieve this remarkable feat, and does their resistance help explain why newts can have enough TTX to immobilize a potential predator 100,000 times its size? Is this some sort of coevolutionary arms race between predator and prey?

Storytelling such as this can be an effective pedagogical tool for increasing cognitive engagement in biology (Carroll, 2018). In this article, I explore one of the world's most lethal neurotoxins, its mysterious origins, and a fascinating arms race between predator and prey. A dynamic evolutionary interaction between garter snakes and newts has produced remarkable adaptations that reveal important biological insights. This scientific tale can be utilized by educators to provide an engaging and authentic backdrop for teaching organismal biology, evolution, genetics, pathophysiology, phylogeny, and much more. As you read this article, consult Table 1 for a summary of topics and suggestions for how each can be used in the classroom.

○ The Mysterious Origin of Tetrodotoxin

Tetrodotoxin (TTX) gets its name from Tetraodontidae, the family that includes the various species of TTX-laden pufferfish. While humans have known since antiquity that pufferfish are toxic (Chau et al., 2011), the chemical was not isolated and purified as a crystal until 1950, first from pufferfish (Yokoo, 1950) and later from the newt genus *Taricha* (Brown & Mosher, 1963). It is now known

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Table 1. A summary of topics related to tetrodotoxin and the coevolutionary arms race between newts and garter snakes, with suggestions for engaging students.

Topic	Learning concept	Student engagement
Molecular attributes of tetrodotoxin (TTX)	Organic chemistry	Interpret organic shorthand notation, identify functional groups, discuss biosynthesis of TTX (Chau et al., 2011).
Evolutionary origin of TTX	Phylogeny and evolution	Create and interpret a phylogenetic tree of organisms that produce TTX (which can be constructed from Chau et al., 2011). Is TTX production a homologous or analogous trait, or neither (Chau et al., 2011)?
Voltage-gated sodium (Na_v) channels	Electrophysiology; protein structure, binding, and inhibition	Discuss normal structure and function of Na_v channels. Explore the effect of TTX on functionality of Na_v channels. Compare the action of TTX to lidocaine, which acts as a noncompetitive antagonist for Na_v channels, as an example of protein-ligand mediated interactions (Sheets & Hanck, 2003; Yu & Catteral, 2003; Jost et al., 2008; Hannifin, 2010; Tikhonov & Zhorov, 2012).
Within a species there are multiple SCN genes, and expression of these genes creates different Na_v channels	Paralogous genes; differential gene expression	What are some potential advantages of gene duplication? Explain why Na_v channels in the brain are unaffected by TTX despite having no TTX-resistant mutations (answer: blood brain barrier) (Yu & Catterall, 2003; Zakon, 2013; McGlothlin et al., 2014; Brodie & Brodie, 2015).
Exogenous production of TTX	Symbiosis; hologenome	What type of symbiotic relationships exist between TTX-producing bacteria and pufferfish and newts? How might the genes between newts and bacterial symbionts (collective referred to as the *hologenome*) be an example of coevolution (Chau et al., 2011; Vaelli et al., 2020)?
Mutations to the SCN genes create novel TTX-resistant Na_v channels	Mutation; protein function; transcription and translation	Why might a missense mutation that changes methionine to threonine inhibit binding of TTX to the Na_v channel? How are the properties of side chains relevant to protein-ligand binding? Is it possible for a mutation to result in no structural or function changes in a protein (Jost et al., 2008; Feldman, et al., 2009; Feldman et al., 2010; Feldman, et al., 2012)?
Snakes, newts, and pufferfish all have similar means of TTX resistance	Convergent evolution	Interpret a phylogenetic tree that demonstrates convergent evolution of TTX resistance. (For examples see Feldman et al., 2009; Hanifin & Gilly, 2015).
Phenotypic matching between garter snakes and toxic newts	Coevolution	What does *reciprocal selection* mean, and how might this play out between toxic newts and predatory snakes (Hague et al., 2020; Reimche et al., 2020)?
Phenotypic mismatching between garter snakes and toxic newts	Geographic mosaic theory of coevolution; gene flow, genetic drift	Why might phenotypic mismatching occur between toxic newts and predatory snakes? What other mechanisms contribute to genetic structure within a population (Hague et al., 2020; Reimche et al., 2020)?

that TTX occurs in a small number of species in at least seven animal phyla (Arthropoda, Chaetognatha, Chordata, Echinodermata, Mollusca, Nemertea, and Platyhelminthes)(Chau et al., 2011) and is used for defense against predators, or in the case of one type of flatworm, to subdue prey (Ritson-Williams et al., 2006). TTX also occurs in some species of dinoflagellates and bacteria (Chau et al., 2011).

TTX (Figure 1) is one of the most potent naturally occurring neurotoxins and is lethal to humans and most other vertebrates (Brodie et al., 2005; Feldman et al., 2010). Its toxicity results from its ability to inhibit transport proteins called voltage-gated Na^+ (Na_v) channels, which are found in the plasma membranes of muscle cells and neurons. Na_v channels are highly conserved among vertebrates and therefore remarkably similar in both structure and function (Brodie et al., 2005; Feldman et al., 2009; Hanifin & Gilly, 2015). TTX binds to the extracellular portion of the channel's pore, which

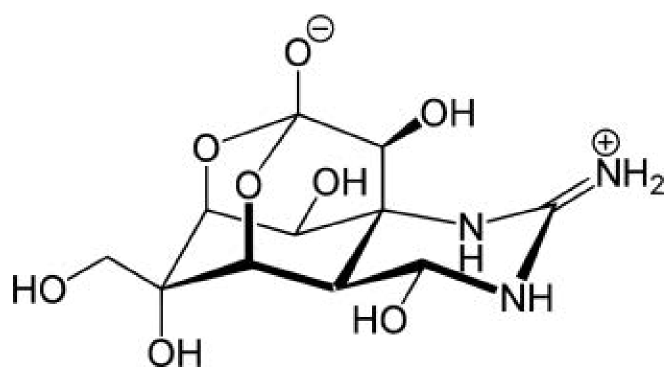

Figure 1. Tetrodotoxin ($C_{11}H_{17}N_3O_8$) acts as a neurotoxin by inhibiting voltage-gated sodium channels. Its exact biosynthesis is unknown (Chau et al., 2011).

impedes the passage of Na^+ and prevents the synthesis of electrical signals called ***action potentials*** (Tikhonov & Zhorov, 2012). Without action potentials, nerve and muscle cells cannot function, which can ultimately lead to paralysis and death (Brodie et al., 2005; Feldman et al., 2009). In humans, death typically occurs in four to eight hours, sometimes as quickly as 20 minutes, and there is no antidote (National Institute for Occupational Safety and Health, 2011).

How exactly TTX is produced is bit of a mystery, which adds the intrigue of this story. The fact that this toxin appears in such widely disparate taxa seems to rule out both homology and convergent evolution (Chau et al., 2011). If TTX production was a trait resulting from homology, it would have arisen long ago in a common ancestor of animals, algae, and bacteria, and thus the trait would have been handed down to a very large number of species, which is not the case. Also, TTX is such a unique and apparently difficult molecule to biosynthesize, it is unlikely that its creation would have independently evolved so many times in widely different animal taxa (Chau et al., 2011).

A more parsimonious hypothesis is that TTX is manufactured by a relatively small number of bacterial species and then bioaccumulates through food webs or is acquired directly via bacterial symbionts (Chau et al., 2011). Such is the case for the pufferfish. TTX-producing bacteria are known to live as symbionts with these fish. In fact, pufferfish that are raised in captivity and fed a controlled diet lose their toxicity over time, suggesting their inability to intrinsically produce the toxin (Noguchi et al., 2006).

Exogenous production of TTX by microbial symbionts, like that occurring in pufferfish, was suspected for all TTX-bearing animal taxa except certain species of toxic newts, most notably the rough-skinned newt (***Taricha granulosa***) (Hanifin, 2010). Endogenous production of TTX in rough-skinned newts was partially supported by the following observations. First, prior to 2020, researchers were unable to isolate and detect TTX-producing bacteria from toxic newts (Chau et al., 2011). Second, ***Taricha*** newts living in captivity increased TTX production over time despite being fed a diet known to decrease TTX production in other toxic animals. Thus, it was apparent that rough-skinned newts did not acquire their TTX through dietary means (Hanifin et al., 2002). Lastly, it appeared that TTX toxicity in newts is subject to evolutionary pressures, suggesting a genetic component related to its production (Brodie et al., 2005).

There are several counterarguments to these claims. First, it was possible that toxic newts did in fact harbor TTX-producing bacteria as symbionts and those bacteria had not yet been detected. It is estimated that only 1% of microbes are culturable (Chau et al., 2011). Thus, the inability to detect TTX-producing bacteria was not proof of their absence. Additionally, any genes acted upon by natural selection may be related to the newt's uptake and storage of bacterially derived TTX, and not from its endogenous production (Hanifin & Gilly, 2015).

Evidence against endogenous production came from a novel isotopic feeding study. ***Taricha*** newts were administered four types of nutrients (acetate, arginine, citrulline, and glucose) constructed from radioisotopes of carbon (^{14}C). These four nutrients were chosen because it was hypothesized that they could be used to create TTX in certain metabolic pathways. Results from the study demonstrated that newts used the ^{14}C to make new metabolites, such as cholesterol derivatives and amino acid derivatives, but none of the ^{14}C was found in newly produced TTX, suggesting that the newts' metabolism was not responsible for its creation (Shimizu & Kobayashi, 1983).

The decades-long mystery of how rough-skinned newts acquired their toxicity was finally settled as I wrote this article. Researchers identified four genera of TTX-producing bacteria living on the skin of rough-skinned newts (Vaelli et al., 2020). ***Pseudomonas*** was one of those four and was especially important in characterizing the difference in microbiomes between the toxic and nontoxic newts included in the study. This research represents the first time that bacterial symbionts capable of producing TTX were identified in anything other than a marine animal species. Subsequently, it now appears that the evolution of toxicity in newts might involve the interplay of genes between the newt and its bacterial symbionts, something referred to as the hologenome (Vaelli et al., 2020).

Despite this breakthrough, a mystery still remains: how do bacteria make TTX? No genes or biosynthetic pathways have yet been identified (Chau et al., 2011). The enigma of TTX production remains to be solved, perhaps by one of your students!

○ Vive la Résistance

With an understanding of TTX and how it acts as a neurotoxin, I can now focus on the evolutionary arms race between toxic newts and the predatory garter snakes that stubbornly resist them. A handful of snake species have evolved resistance to TTX. How did they achieve this, and are these traits due to shared ancestry (homology) or convergent evolution (analogy)?

Molecular Basis of TTX Resistance

Students in introductory biology and physiology courses study electrical signaling and thus learn about Na_v channels. What they might not know is that all animals have these channels and the channels share genetic and structural similarities (Yu & Catterall, 2003). This is because Na_v channels are a homologous trait inherited from a common ancestor of animals that lived approximately 650 million years ago (Zakon, 2013). Na_v channels were critically important in the evolution of animals because of their central role in the development of the nervous system (Zakon, 2013).

Na_v channels are membrane proteins made of a single alpha subunit and one or more beta subunits (Yu & Catterall, 2003). The alpha subunit and its four domains are arguably the most important, as they contain the pore and gate that regulate diffusion of Na^+ into cells, thereby initiating an action potential. Interestingly, TTX played an important role in how scientists came to understand the structure and function of Na_v channels (Yu & Catterall, 2003). As previously noted, TTX inhibits Na_v channels by interfering with the diffusion of Na^+. Researchers used the ability of TTX to bind to these protein channels as a way of exploring the amino acid sequence of key structural segments (reviewed in Hanifin & Gilly, 2015).

For vertebrates, the genetic instructions for Na_v type 1 (hereafter Na_v1, with decimals denoting subtypes) channels reside in the SCN gene family, which codes for the alpha subunit of the channel protein complex. The number of genes in this family vary by taxa, from two in lamprey to ten in mammals (Zakon, 2013). Genes in the SCN family were created through multiple gene duplication events and now code for slightly different Na_v1 channels (Zakon, 2013), with the different types often expressed in different tissues (Brodie & Brodie, 2015).

Genes created through gene duplication can diverge from one another over time and can take on new functions; such genes are described as paralogous. In mammals and reptiles, for example, there are nine functional paralogous genes that code for nine types of voltage-gated sodium channels (as previously noted there are ten genes in mammals, but one of these, Na_x, has mutated and taken on a new function as a salt sensor) (Hiyama et al., 2002; Yu & Catterall, 2003). Students might be interested to know that in humans, mutations in these genes can result in such disorders as epilepsy (National Institutes of Health, 2020a), periodic paralysis, and muscle weakness (National Institutes of Health, 2020b).

Interestingly, some Na_v channels are naturally resistant to TTX or otherwise protected from it. In snakes (and similarly in humans), tests have demonstrated that channel subtypes $Na_v1.1$, $Na_v1.2$, and $Na_v1.3$ are sensitive to TTX (Yu & Catterall, 2003). However, because they are expressed in the central nervous system, they are normally protected by the blood-brain barrier, which prevents TTX from entering that nervous tissue and impairing the channels (McGlothlin et al., 2014; Brodie & Brodie, 2015). $Na_v1.5$ channels are expressed in heart muscle and are naturally resistant to TTX, as are the Na_v 1.8 and $Na_v1.9$ channels of the peripheral nervous system (PNS). Lastly, the remaining three varieties of channels are susceptible to TTX: $Na_v1.4$, found in skeletal muscle tissue, and $Na_v1.6$ and $Na_v1.7$ found in the PNS (Brodie & Brodie, 2015).

Thus, to resist succumbing to the effects of TTX, both newts and garter snakes require mutations in the $Na_v1.4$, $Na_v1.6$, and $Na_v1.7$ channels, with the Nav1.4 channel being especially critical for its role in controlling muscle movement and breathing.

Common Solutions

Resistance to TTX has developed repeatedly in multiple animal taxa, among both predators and prey. It is important to recognize that prey, such as newts and pufferfish, also require resistance to TTX because their Na_v channels are just as susceptible as those in snakes, humans, or any other vertebrate. What is remarkable is that TTX resistance has independently evolved multiple times through convergent evolution, and animals such as newts, snakes, and pufferfish have all arrived at a common solution.

That solution involves mutated SCN genes that produce amino acid substitutions and structural changes in Na_v channels (Figure 2). These changes reduce the ability of TTX to bind to Na_v channels by physically blocking TTX or disrupting normal electrostatic attractions with it, such as hydrogen bonds (Feldman et al., 2012). Approximately 80 amino acids compose the region of the outer (extracellular) pore where TTX binds to Na_v channels (Tikhonov & Zhorov, 2012) and it takes as little as a single amino acid substitution in this region to substantially reduce the binding affinity of TTX (Feldman et al., 2009). For example, compared to the ancestral condition, the Sierra garter snake (*Thamnophis couchii)* has an amino acid substitution in domain III of the $Na_v1.4$ channel that replaced a methionine and its hydrophobic side chain with a hydrophilic threonine (Feldman et al., 2009). This very same mutation developed in toxic pufferfish and rough-skinned newts through convergent evolution. Studies of this particular amino acid substitution found that it increased resistance to TTX by a factor of 15 (Jost et al., 2008).

While I just highlighted the effects of just a single mutation, species with TTX resistance often have several mutations in the outer pore of Na_v channels. For example, rough-skinned newts can have three missense mutations (resulting in three amino acid substitutions) in the outer pore region of the $Na_v1.6$ channel. Each mutation independently contributes to TTX resistance, and the additive effect of all three is extreme resistance (Vaelli et al., 2020). Similarly, TTX resistance increases in garter snakes with an increasing number of mutations (Feldman et al., 2009; Feldman et al., 2010). Overall, it is remarkable that taxonomically diverse species have independently evolved such similar solutions to resisting TTX through modification of the outer pore of Na_v channels (Figure 3). In some cases, snakes, newts, and pufferfish have convergently evolved the same amino acid substitutions in their Na_v channels.

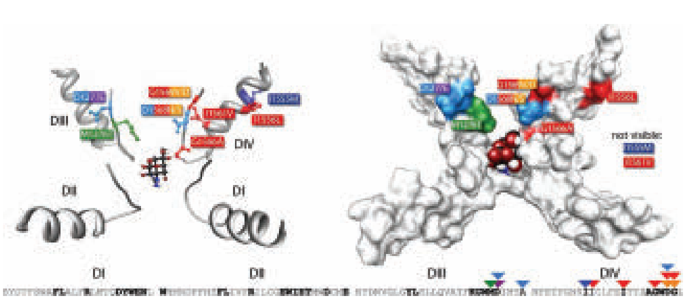

Figure 2. The outer pore of $Na_v1.4$ channel is shown in two models. In the middle of each is tetrodotoxin. The models also indicate how mutations have produced multiple amino acid substitutions among several species. Shown at the bottom of this figure is the amino acid sequence for the four $Na_v1.4$ domains, with amino acids known to affect TTX binding shown in bold and mutations found in some snake species indicated with triangles. Figure taken from Feldman et al., 2012.

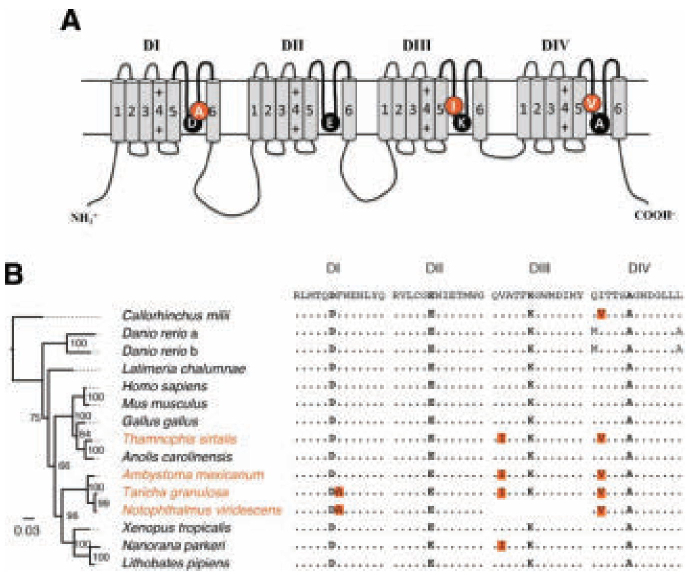

Figure 3. Convergent evolution of TTX resistance. (**A**) The four domains of $Na_v1.6$ are shown, with amino acid substitutions that confer TTX resistance shown in lighter shading. (**B**) A phylogeny for select species along with amino acid sequence alignments of the four $Na_v1.6$ domains. Included are the rough-skinned newt (*Taricha granulosa*) and the common garter snake (*Thamnophis sirtalis*). Lighter font indicates TTX-resistant species and lighter shading denotes substitutions that provide TTX resistance. Figure taken from Vaelli et al., 2020, which is licensed under a Creative Commons Attribution license.

○ Coevolution

Many students are likely familiar with the concept of predator-prey arms races due to watching nature documentaries. What makes this case study interesting to students is that newts and garter snakes are potentially common "backyard" species, especially for those living along the western coast of the United States. Thus, the newt/snake arms race may be a more accessible and regionally relevant example of coevolution than what is typically presented in documentaries.

The coevolutionary arms race between garter snakes and toxic newts is well established (Brodie &Brodie, 1990) and is defined by iterations of adaptation and counteradaptation (Janzen, 1980; Brodie et al., 2005; Hague et al., 2020; Reimche et al., 2020). Newts evolved the capacity to use TTX as an antipredator defense, whereas predatory garter snakes evolved resistance to TTX in a process of reciprocal selection (Hague et al., 2020). Presumably, newts that could fortify their bodies with TTX had a selective advantage due to reduced predation. In response, snakes with TTX resistance had a selective advantage because they survived when preying on toxic newts and got a tasty meal out of it. Consequently, in some areas newts have extremely high TTX levels (enough to kill 50 people) and garter snakes have extreme TTX resistance.

Analyzing geographic variations of phenotypes is presently the leading method used by ecologists to validate the coevolutionary link between populations of rough-skinned newts and garter snakes (Figure 4). These ecologists have investigated such questions as "Does TTX resistance in snake populations increase in areas where newts are more toxic?", and "When toxic newts are absent, do snake populations have low TTX resistance?" For the common garter snake (*Thamnophis sirtalis*) and the rough-skinned newt (*T. granulosa*) in particular, the coevolutionary arms race is well documented. Biologists have discovered that substantial intraspecific variation exists for both TTX levels in *T. granulosa* and TTX resistance in *T. sirtalis,* and these two traits strongly covary across the US West Coast (Hague et al., 2020). When newts produce high levels of TTX, garter snakes tend to have high resistance, and the opposite is also true (Hague et al., 2020; Reimche et al., 2020). Similar geographic patterns of phenotypic matching have also been found between the Sierra garter snake (*T. couchii*) and three toxic newt species within the *Taricha* genus (Reimche et al., 2020). Considered together, these parallel cases provide compelling evidence for the coevolutionary relationship between TTX production in prey and TTX resistance in predators.

However, phenotypes between newts and garter snakes do not always match (Figure 4C) (Brodie et al., 2005). For example, certain populations of *T. couchii* and *T. sirtalis* exhibit extreme TTX resistance despite relatively low levels of TTX in sympatric newts (Hague et al., 2020; Reimche et al., 2020). This suggests that the snakes might have "won" the arms race by being able to withstand extremely high levels of TTX (Reimche et al., 2020). To explain such a mismatch, we can hypothesize that having TTX would no longer produce a selective advantage for newts once snakes evolved extreme resistance and natural selection might favor newt phenotypes with reduced TTX levels, especially if having TTX comes at a cost. One cost for newts could be the energetic demands of TTX biosynthesis, even with bacterial symbionts producing it (Hanifin, 2010). Other costs are associated with the fact that, like snakes, newts must be resistant to TTX. Evidence suggests that the structural changes that made Na_v channels TTX resistant also resulted in reduced operability of the channels (Lee et al., 2011), which in turn results in reduced speed of organismal locomotion in newts (Brodie et al., 2005). Meanwhile, we might also hypothesize that natural selection in garter snakes favors extreme TTX resistance because it could lower their own mortality from predators. As snakes feed on newts, they accumulate TTX and become poisonous themselves. Studies indicate that snakes can sequester TTX from newts in their kidneys for three weeks and in the liver for at least seven weeks (Williams et al., 2004).

Another example of phenotypic mismatching occurs in areas of Alaska where the predatory *T. sirtalis* is absent yet populations of rough-skinned newts exhibit surprising diversity in TTX toxicity, with most producing low levels of TTX but some producing high levels (Hague et al., 2016). In this circumstance, levels of TTX in newts is not being driven by reciprocal selection with predatory snakes. In this and other cases of phenotypic mismatching, population structure of traits may be attributed to mechanisms such as genetic drift, gene flow, and differences in prey abundance, which are concordant with the geographic mosaic theory of coevolution (Hague et al., 2016; Reimche et al., 2020).

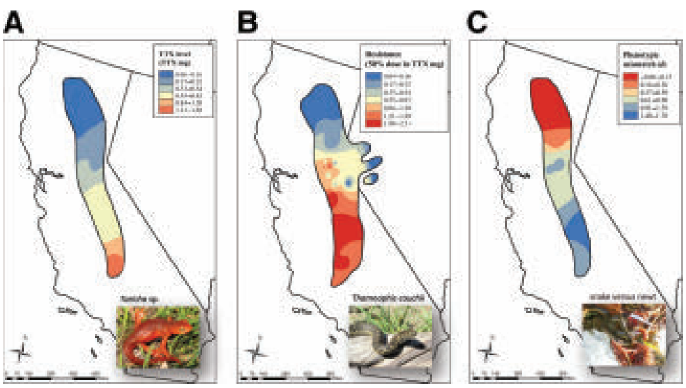

Figure 4. Evolutionary ecologists map trait variation at the population level to find evidence of coevolution: (**A**) TTX levels in prey (*Taricha* newts), (**B**) TTX resistance in predator (Sierra garter snake), and (**C**) phenotypic mismatch between newts and snakes. Warm colors denote higher levels of TTX, TTX resistance, and phenotypic matching, respectively. Figure taken with permission from Reimche et al., 2020; copyright 2020 British Ecological Society.

○ Experimentation & Biotechnology

Some argue that it is more important for students to learn the scientific process than scientific facts (National Science Board, 2008). This case study in coevolution provides many opportunities for educators to discuss, and perhaps demonstrate, the biotechnology and experimental methods used by researchers (Table 2). For example, genetic analysis was critical for elucidating the mechanism and convergent evolution of TTX resistance. Educators can replicate this process for their students by extracting and amplifying DNA (preferably from nonpoisonous sources and without harming any vertebrates), and perhaps even sequencing the DNA. Similarly, students can use publicly available bioinformatics databases like BLAST to compare DNA or protein sequences for Na_v channels among different species.

While such DNA analysis may seem relatively straightforward from a conceptual standpoint, students might be perplexed about other parts of the research presented here. For example, how did

Table 2. Summary of the scientific processes used to understand TTX resistance and toxicity, and the coevolution of both traits. Discussing these processes within the context of newt and garter snake coevolution can help students better understand the process of science.

Process of science	Details
Radioisotopic feeding studies	Use of carbon radioisotopes to determine if newts synthesized TTX (Shimizu & Kobayashi, 1983).
Quantifying TTX levels	Determining TTX levels in newts using high-performance liquid chromatography, mass spectrometry, (Brodie et al., 2005; Vaelli et al., 2020), and competitive inhibition enzymatic immunoassay with TTX-specific antibodies (Hague et al., 2020; Reimche et al., 2020).
Comparing DNA and protein sequences in SCN genes and Na_v channels, respectively	DNA extraction, polymerase chain reaction, DNA sequencing, and alignment of DNA and computer-translated amino acid sequences (e.g., Feldman et al., 2010; Hanifin & Gilly, 2015; Vaelli et al., 2020).
Determining toxic effect of TTX (molecular scale)	Measuring changes in membrane potential in genetically engineered cells expressing either normal or resistant version of Na_v channels, following exposure to TTX (Geffeney et al., 2005; Jost et al., 2008).
Determining toxic effect of TTX (organismal scale)	Whole-organism bioassay involves injections of TTX to determine effect on speed of locomotion in garter snakes (Brodie et al., 2005; Feldman et al., 2009).
Phylogenetic analysis of Na_v protein sequences	Amino acid sequences are compared among various types of animals to assess convergent evolution of TTX resistance (Feldman et al., 2009; Hanifin & Gily, 2015; Hague et al., 2017)
Determining population structure and geographically analyzing the distribution of traits among prey and predators	Sample populations for traits of interest (genetic variation, TTX resistance, etc.), map the distribution of these traits for both prey and predators, and use models and statistical analysis to test for covariance (Brodie et al., 2002; Hague et al., 2016; Hague et al., 2020; Reimche et al., 2020).

biologists determine that "an amino acid substitution in domain III of the $Na_v1.4$ channel … increases resistance to TTX by a factor of 15"? Genetic analysis can determine if and where amino acids substitutions occurred, but how did the researchers determine the effect of a mutation on the phenotype (in this case, TTX resistance)?

Answering that question can be enlightening for students. In short, scientists quantified TTX resistance by measuring changes in membrane potential, first in normal cells and then in cells having the mutated (TTX-resistant) form of Na_v channels, such as those found in some garter snakes. Na_v channels normally produce changes in membrane potential by allowing the diffusion of Na^+ into the cell. As Na^+ enters the cell, membrane potential becomes more positive and this helps create action potentials. In species susceptible to TTX, such has humans, the toxin binds to Na_v channels and this reduces or stops the influx of Na^+, which results in little or no change in membrane potential. This is harmful to the organism because without that change, action potentials cannot be created. Scientists can use the patch clamp technique (Neher & Sakman, 1992) to measure changes in membrane potential (or lack thereof) in a single cell following exposure to TTX. Thus, they can quantify the impact that TTX has on the functionality of Na_v channels. A mutated Na_v channel from garter snakes that is resistant to TTX would demonstrate normal changes in membrane potentials despite the presence of TTX.

Interestingly, scientists used genetically engineered frog cells to conduct these tests (Jost et al., 2008). Rat skeletal muscle was the source of cDNA for creating the normal, TTX-susceptible $Na_v1.4$ channel. Using a process called site-directed mutagenesis, the rat cDNA was mutated to introduce the necessary amino acid substitution to create a TTX-resistant form of the channel, like that found in some garter snakes. These two versions of the gene were then injected into different *Xenopus* oocytes in the form of synthetic RNA transcripts (called cRNA). There, the cRNA was expressed to create either the normal or mutated version of $Na_v1.4$ channels (Jost et al., 2008).

A similar process using genetically engineered *Xenopus* oocytes was used to determine TTX resistance in rough-skinned newts, with a couple notable differences. First, the DNA was sourced from the mouse *Mus musculus* instead of rats. And second, site-directed mutagenesis introduced three amino acid substitutions to match those found in rough-skinned newts (Vaelli et al., 2020).

TTX resistance in garter snakes can also be determined using a whole-organism bioassay. This technique involves intraperitoneal injections of TTX to determine any negative impact on locomotion. Snakes that move more slowly exhibit TTX susceptibility, where those that are resistant are unaffected (Brodie et al., 2005; Feldman et al., 2009). Through analysis of both techniques mentioned here (whole-organism bioassays and bioengineered cellular testing), educators can facilitate discussions with students about why scientists might choose to answer the same research question by looking at different scales of biological organization. Students might also consider the pros and cons of each method.

Making connections between the scientific facts and the scientific process can be enlightening for students. Whether using liquid chromatography and mass spectrometry to quantify TTX levels or a DNA sequencer to find mutations in SCN genes, students can benefit when connections are made between course content and real-world world applications (Brown et al., 2009).

○ Conclusion

Biology students learn about genetics, membrane proteins, electrical signaling, evolution, and more. These can be taught as isolated facts, or they can be woven together into a story that demonstrates the connections between them, provides context, and highlights the application of such information. The story of coevolution between newts and garter snakes can assist educators by providing a cogent and multifaceted backdrop for engaging students in fundamental concepts in biology.

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References

Brodie, E.D., III & Brodie, E.D., Jr. (1990). Tetrodotoxin resistance in garter snakes: an evolutionary response of predators to dangerous prey. *Evolution*, *44*(3), 651–59.

Brodie, E.D., III & Brodie, E.D., Jr. (2015). Predictably convergent evolution of sodium channels in the arms race between predators and prey. *Brain, Behavior, and Evolution*, *86*, 48–57.

Brodie, E.D., III, Feldman, C.R., Hanifin, C.T., Motychak, J.E., Mulcahy, D.G., Williams, B.L. & Brodie, E.D., Jr. (2005). Parallel arms races between garter snakes and newts involving tetrodotoxin as the phenotypic interface of coevolution. *Journal of Chemical Ecology*, *31*, 343–56. https://doi.org/10.1007/s10886-005-1345-x.

Brodie. E.D., Jr., Ridenhour, B.J. & Brodie, E.D., III. (2002). The evolutionary response of predators to prey: hotspots and coldspots in the geographic mosaic of coevolution between garter snakes and newts. *Evolution*, *56*(10), 2067–82.

Brown, M.K., Hershock, C., Finelli, C.J. & O'Neal, C. (2009). Teaching for retention in science, engineering, and math disciplines: a guide for faculty. *CRLT Occasional Papers*, #25. http://crlt.umich.edu/sites/default/files/resource_files/CRLT_no25.pdf.

Brown, M.S. & Mosher, H.S. (1963). Tarichatoxin: isolation and purification. *Science*, *140*, 295–96.

Carroll, S.B. (2018). The power and place of stories in biology class. *American Biology Teacher*, *80*(8), 557–59.

Chau, R., Kalaitzis, J.A. & Neilan, B.A. (2011). On the origins and biosynthesis of tetrodotoxin. *Aquatic Toxicology*, *104*, 61–72.

Feldman, C.R., Brodie, E.D., Jr., Brodie, E.D., III & Pfrender, M.E. (2009). The evolutionary origins of beneficial alleles during the repeated adaptation of garter snakes to deadly prey. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(32), 13415–20. https://doi.org/10.1073/pnas.0901224106.

Feldman, C.R., Brodie, E.D., Jr., Brodie, E.D., III & Pfrender, M.E. (2010). Genetic architecture of a feeding adaptation: garter snake (*Thamnophis*) resistance to tetrodotoxin bearing prey. *Proceedings of the Royal Society B*, *277*(1698), 3317–25. https://doi.org/10.1098/rspb.2010.0748.

Feldman, C.R., Brodie, E.D., Jr., Brodie, E.D., III & Pfrender, M.E. (2012). Constraint shapes convergence in tetrodotoxin-resistant sodium channels of snakes. *Proceedings of the National Academy of Sciences USA*, *109*, 4556–61.

Feldman, C.R., Durso, A.M., Hanifin, C.T., Pfrender, M.E., Ducey, P.K., Stokes, A.N., Barnett, K.E., Brodie, E.D., III & Brodie, E.D., Jr. (2016). Is there more than one way to skin a newt? Convergent toxin resistance in snakes is not due to a common genetic mechanism. *Heredity*, *116*(1), 84–91. https://doi.org/10.1038/hdy.2015.73.

Geffeney, S., Fujimoto, E., Brodie, E.D., III, Brodie, E.D., Jr. & Ruben, P.C. (2005). Evolutionary diversification of TTX-resistant sodium channels in a predator–prey interaction. *Nature*, *434*, 759–63. https://doi.org/10.1038/nature03444.

Hague, M.T.J., Avila, L.A., Hanifin, C.T., Snedden, W.A., Stokes, A.N., Brodie, E.D., Jr. & Brodie, E.D., III. (2016). Toxicity and population structure of the rough-skinned newt (*Taricha granulosa*) outside the range of an arms race with resistant predators. *Ecology and Evolution*, *6*(9), 2714–24. https://doi.org/10.1002/ece3.2068.

Hague, M.T.J., Feldman, C.R., Brodie, E.D., Jr., & Brodie, E.D., III. (2017). Convergent adaptation to dangerous prey proceeds through the same first-step mutation in the garter snake *Thamnophis sirtalis*. *Evolution*, *71*(6), 1504–18. https://doi.org/10.1111/evo.13244.

Hague, M.T.J., Stokes, A.N., Feldman, C.R., Brodie, E.D., Jr. & Brodie, E.D., III. (2020). The geographic mosaic of arms race coevolution is closely matched to prey population structure. *Evolution Letters*, *4-4*, 317–32. https://onlinelibrary.wiley.com/doi/full/10.1002/evl3.184.

Hanifin, C.T. (2010) The chemical and evolutionary ecology of tetrodotoxin (TTX) toxicity in terrestrial vertebrates. *Marine Drugs*, *8*(3), 577–93.

Hanifin, C.T., Brodie, E.D., III & Brodie, E.D., Jr. (2002). Tetrodotoxin levels of the rough-skin newt, *Taricha granulosa*, increase in long-term captivity. *Toxicon*, *40*, 1149–53.

Hanifin, C.T. & Gilly, W.F. (2015). Evolutionary history of a complex adaptation: tetrodotoxin resistance in salamanders. *Evolution*, *69*(1), 232–44. https://doi.org/10.1111/evo.12552.

Hiyama T.Y., Watanabe, E., Ono, K., Inenaga, K., Tamkun, M.M., Yoshida, S. & Noda, M. (2002). Na_x channel involved in CNS sodium-level sensing. *Nature Neuroscience*, *5*, 511–12. https://doi.org/10.1038/nn856.

Janzen, D.H. (1980). When is it coevolution? *Evolution*, *34*, 611–612.

Jost, M.C., Hillis, D.M., Lu, Y., Kyle, J.W., Fozzard, H.A. & Zakon, H.H. (2008). Toxin-resistant sodium channels: parallel adaptive evolution across a complete gene family. *Molecular Biology and Evolution*, *25*(6), 1016–24. https://doi.org/10.1093/molbev/msn025.

Lee, C.H., Jones, D.K., Ahern, C., Sarhan, M.F. & Ruben, P.C. (2011). Biophysical costs associated with tetrodotoxin resistance in the sodium channel pore of the garter snake, *Thamnophis sirtalis*. *Journal of Comparative Physiology*, *197*(1), 33–43. https://doi.org/10.1007/s00359-010-0582-9.

McCurry, J. (2016). Last supper? Japan's diners divided over killer puffer fish. *The Guardian*. www.theguardian.com/world/2016/aug/05/last-supper-japan-killer-puffer-fish-fugu.

McGlothlin, J.W., Chuckalovcak, J.P., Janes, D.E., Edwards, S.V., Feldman, C.R., Brodie, E.D., Jr., Pfrender, M.E. & Brodie, E.D., III. (2014). Parallel evolution of tetrodotoxin resistance in three voltage-gated sodium channel genes in the garter snake *Thamnophis sirtalis*. *Molecular Biology and Evolution*, *31*(11), 2836–46.

National Institute for Occupational Safety and Health. (2011). Tetrodotoxin: biotoxin. NIOSH. https://www.cdc.gov/niosh/ershdb/emergencyresponsecard_29750019.html.

National Institutes of Health. (2020a). SCN1A gene. NIOSH. https://ghr.nlm.nih.gov/gene/SCN1A#conditions.

National Institutes of Health. (2020b). SCN4A gene. NIOSH. https://ghr.nlm.nih.gov/gene/SCN4A#conditions.

National Science Board. (2008). *Science and Engineering Indicators 2008*. Two volumes. Arlington, VA: National Science Foundation.

Neher, E. & Sakmann, B. (1992). The patch clamp technique. *Scientific American*, *266*(3), 44–51. www.jstor.org/stable/24938980.

Noguchi, T., Arakawa, O. & Takatani, T. (2006). Toxicity of pufferfish *Takifugu rubripes* cultured in netcages at sea or aquaria on land. *Comparative Biochemistry and Physiology. Part D, Genomics & Proteomics*, *1*, 153–57.

Reimche, J.S., Brodie, E.D., Jr., Stokes, A.N., Ely, E.J., Moniz, H.A., Thill, V.L., Hallas, J.M., Pfrender, M.E., Brodie, E.D., III & Feldman, C.R. (2020). The geographic mosaic in parallel: matching patterns of newt tetrodotoxin levels and snake resistance in multiple predator-prey pairs. *Journal of Animal Ecology*, *89*(7), 1645–57.

Ritson-Williams, R., Yotsu-Yamashita, M. & Paul, V.J. (2006). Ecological functions of tetrodotoxin in a deadly polyclad flatworm. *Proceedings of the National Academy of Sciences USA*, *103*(9), 3176–79. https://pubmed.ncbi.nlm.nih.gov/16492790/.

Sheets, M.F. & Hanck, D.A. (2003). Molecular action of lidocaine on the voltage sensors of sodium channels. *Journal of General Physiology*, *121*(2), 163–75. https://doi.org/10.1085/jgp.20028651.

Shimizu, Y. & Kobayashi, M. (1983). Apparent lack of tetrodotoxin biosynthesis in captured *Taricha torosa* and *Taricha granulosa*. *Chemical and Pharmaceutical Bulletin*, *31*, 3625–31.

Tikhonov, D.B & Zhorov, B.S. (2012). Architecture and pore block of eukaryotic voltage-gated sodium channels in view of NavAb bacterial sodium channel structure. *Molecular Pharmacology*, *82*, 97–104.

Vaelli, P.M., Theis, K.R., Williams, J.E., O'Connell, L.A., Foster, J.A. & Eisthen, H.L. (2020). The skin microbiome facilitates adaptive tetrodotoxin production in poisonous newts. *eLife*, *9*, e53898. https://doi.org/10.7554/eLife.53898.

Williams, B.L., Brodie, E.D., Jr. & Brodie, E.D., III. (2004). A resistant predatory and its toxic prey: persistence of newt toxin leads to poisonous (not venomous) snakes. *Journal of Chemical Ecology*, *30*(10), 1901–19.

Yasumoto, T. and Yotsu-Yamashita, M. (1996). Chemical and etiological studies on tetrodotoxin and its analogs. *Toxin Reviews*, *15*, 81–90.

Yokoo, A. (1950). Study on chemical purification of tetrodotoxin (3)-purification of spheroidine. *Journal of Chemical Society of Japan*, *71*, 590–92.

Yu, F.H. & Catterall, W.A. (2003). Overview of the voltage-gated sodium channel family. *Genome Biology*, *4*, 207. https://genomebiology.biomedcentral.com/articles/10.1186/gb-2003-4-3-207.

Zakon, H.H. (2013). Adaptive Evolution of Voltage-Gated Sodium Channels: The First 800 Million Years. In G.F. Striedter, J.C. Avise & F.J. Ayala (Eds.), *In the Light of Evolution: Volume VI: Brain and Behavior*. Washington DC: National Academies Press. https://www.ncbi.nlm.nih.gov/books/NBK207163.

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BioInteractive's Free Online Professional Learning Course on Evolution: Overview & Evaluation

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Abstract

Teachers are eager for professional development on teaching evolution, especially if it includes direct ties to relevant curricula and detailed lesson plans. Howard Hughes Medical Institute's BioInteractive Online Professional Learning: Evolution course was developed to provide educators with free, in-depth, multimedia resources that highlight important scientific concepts and studies in evolution and engage participants through interactive activities that link to student resources. Our goals in the development of the asynchronous, nonfacilitated course were to (1) deepen teachers' content knowledge of evolutionary concepts essential to NGSS and AP Biology courses, (2) increase teachers' confidence and comfort in teaching evolution content to general biology and AP Biology students, (3) have teachers identify major evolutionary concepts in scientific studies, authentic data, or educational media used to teach evolution, and (4) assist teachers in identifying and incorporating relevant BioInteractive resources to illustrate evolutionary content and science practices in their own course(s). Our results from a postcourse survey that included pre-post retrospective confidence questions suggest that the course improved educators' knowledge in evolution and their confidence in teaching evolutionary topics. Overall, this course provides educators the opportunity to deepen their content knowledge and obtain exciting, relevant, and reliable resources to use in their classrooms.

Key Words: *evolution; professional development; online course.*

○ Introduction

The BioInteractive Online Professional Learning: Evolution course, first published in 2018 and revised in 2019, is designed to support teachers in deepening their content knowledge in biological evolution and provide them with valuable classroom tools. Understanding biological evolution is essential for biological literacy and supporting teachers in teaching evolution is critical. The course introduces teachers to free, high-quality classroom multimedia resources from BioInteractive that are grounded in the process of science and data and use engaging stories to illustrate scientists' work and motivations. The online, asynchronous, nonfacilitated course consists of three units, which teachers can take in a prescribed sequence to earn a certificate that can be applied to professional development (PD) hours or a noncertificate option in which they can access any lesson of their choosing.

Both the evolution education literature and our firsthand interactions and BioInteractive's surveys of teachers suggested teachers want a PD course that provides opportunities to learn more about evolution (e.g., Friedrichsen et al., 2016; Sanders & Ngxola, 2009). Evolution was ranked as one of the top three choices among eight biology content topics by 79% of 57 teachers surveyed by BioInteractive in 2015 at the National Science Teachers Association (NSTA) national conference. However, most science teachers have reported that they are more often given opportunities for generic PD as opposed to science-specific PD, let alone PD on evolution in particular (Luft et al., 2009). Providing access to relevant curricula and detailed lesson plans for teaching evolution is also critical (e.g., Friedrichsen et al., 2016; Griffith & Brem, 2004). The 276 Missouri teachers studied by Friedrichsen and colleagues (2016) reported a lack of good lab activities and supplemental materials as their two biggest obstacles to teaching evolution. Lessons that specifically support students in using the practices of science—such as analyzing and interpreting data, constructing explanations, and engaging in arguing from evidence—may be particularly useful (e.g., Johnson & Lark, 2018). Asynchronous, online PD from a trusted, stable provider like Howard Hughes Medical Institute (HHMI) BioInteractive and grounded in lessons that incorporate actual scientific research and integrate the practices of science is scalable and may help address these PD needs. Out of the 57 high school biology teachers surveyed at NSTA in 2015 by BioInteractive, 54 said they would consider taking an asynchronous course.

Evolution education researchers outline other needs that drove the development of the online course. Prior research suggests teachers would benefit from experiences that help them reflect on and build their content knowledge (e.g., Ha et al., 2015; Kim & Nehm, 2011; Nehm et al., 2009; Nunez et al., 2012). For example, research by Plutzer and colleagues (2020), who administered and analyzed a nationally representative survey to 752 high school biology teachers in 2019 concerning teaching evolution, suggested that 46% of biology teachers did not complete a college course with an

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evolution focus, 62% completed two or fewer courses with some evolution, and 68% have never taken a PD course with an evolution focus. Teachers also need more experience with the specific strategies for implementing lessons on biological evolution, especially concerning specific patterns of students' prior knowledge and misconceptions, curricula, and instructional strategies (Sickel & Friedrichsen, 2013) to help build their confidence (Hawley & Sinatra, 2019). Encouragingly, the research by Plutzer and colleagues (2020) suggests that increases in teacher participation in PD for evolution leads to improvements in the teaching of evolution and to an increase in the number of teachers teaching evolution as settled science, particularly for veteran teachers and those in NGSS states. Ha and colleagues (2015) suggest evolution-focused PD can have long-lasting effects.

In this paper, we provide an overview of the design and content of the course we developed in response to these needs, with an emphasis on our design principles. We then outline key features of the course. In the final section, we summarize evaluation data provided by teachers completing the first version of the course. Part of the evaluation focused on teachers' confidence in teaching evolution which, as described previously, can be a barrier to implementation (Hawley & Sinatra, 2019). These data were used to relaunch the courses in October of 2019 and enabled us to modify the course to better meet the needs of the educators. Hopefully, lessons from this evaluation will be useful to other providers of online PD.

○ Overview of the Course

Course Content

The teacher learning goals for the course are that by the end of the course, teachers will

- deepen their content knowledge of evolutionary concepts that are essential to NGSS and AP Biology courses;
- increase their confidence and comfort in teaching evolution content to general biology and AP Biology students;
- identify major evolutionary concepts in scientific studies, authentic data, or educational media used to teach evolution; and
- identify and incorporate relevant BioInteractive resources to illustrate evolutionary content and science practices in their own courses.

This course consists of three units, and the total time required for the entire course is estimated to be 15 hours. Unit 1 focuses on the mechanisms of evolution. It includes how to build an explanation based on evidence for natural selection. Unit 2 focuses on sources of evidence supporting evolutionary theory, including fossils, anatomy, biochemistry, genetics, and cell biology. Unit 3 focuses on patterns of evolution, including phylogenies and macroevolution. The units are divided into varying numbers of lessons (see Supplemental Data, Table S1, available with the online version of this article). Each lesson includes informational readings and videos and provides activities for participants to apply what they learn.

Design Principles

Although much remains to be learned about effective science PD, especially about biological evolution and online PD, we considered the following PD design features generally recommended by education researchers (e.g., Desimone, 2009; Ha & Nehm, 2015; Wilson, 2013) that are attainable in an asynchronous, nonfacilitated course. (1) Participants should engage as active learners with the course content. (2) The content of the course should be relevant to participants and the learners they teach. (3) Similarly, participants should be given a chance to reflect on the content as both learners and teachers, especially how the content can be incorporated into their specific context. (4) The content should be coherent with standards, in this case aspects of evolutionary biology that are a part of the Next Generation Science Standards (NGSS) and AP Biology, and teachers should reflect on how the content ties to the standards. The content is also relevant for teachers of International Baccalaureate Biology, honors biology, or middle school biology. Although we could not assure other recommended features (collective participation or activities and reflection of sufficient duration), it is possible to use the course to align with those features too. For example, during the 2018–2019 school year, 18 teachers in *Math for America* participated in the online course together over a four-month period where they met monthly. In these meetings, teachers reflected as a group on their implementation of the activities and presented on a lesson from the course that they used with their students, including the modifications they made to best suit their student population. We encourage course exploration as a community to enhance learning through interacting with peers and gaining insights from one another (Hord, 2004; Spillane & Louis, 2002).

We designed the course with features for effective science PD by including activities that are closely aligned to teachers' practice, immersing teachers in inquiry experiences and ensuring that curriculum materials are educative for teachers and transferable to their students. We also included instruction on specific teaching innovations, in this case integrating science practices and evolutionary biology content (Wilson, 2013). A final recommendation from the literature is taking participants' physical and psychological comfort into account. This was accomplished by making the course online, asynchronous, and free.

Course Features

Interactive, engaging media. BioInteractive hosts a large range of high-quality short films, virtual labs, and online interactives grounded in contemporary science and field-tested in the classroom. Selected segments from the short films and activities are implemented throughout the course with follow-up questions and tasks for adult learners. For example, teachers use a modified version of BioInteractive's Lizard Evolution Virtual Lab to investigate how anole lizard populations change over time in response to different environments. They are given a scenario in which lizards from a relatively large island with varied vegetation and large trees are placed on islands that lack lizards and have only small bushes and grass.

Teachers first describe the variation in leg and body length in the large island lizard population with a "virtual ruler" that allows them to measure these characteristics on X-rays from anoles used in the actual research study (Figure 1). Measuring these traits allows teachers to actively participate in data collection. Teachers determine the ratio of hind-limb length to body length, and the resulting sample data is subjected to statistical analysis. Videos and slides display step-by-step instructions on how the sample mean, standard deviation, standard error of the mean, and 95% confidence intervals are calculated. Later on, the traits of lizards from the experimental islands are compared to those on the larger island to investigate

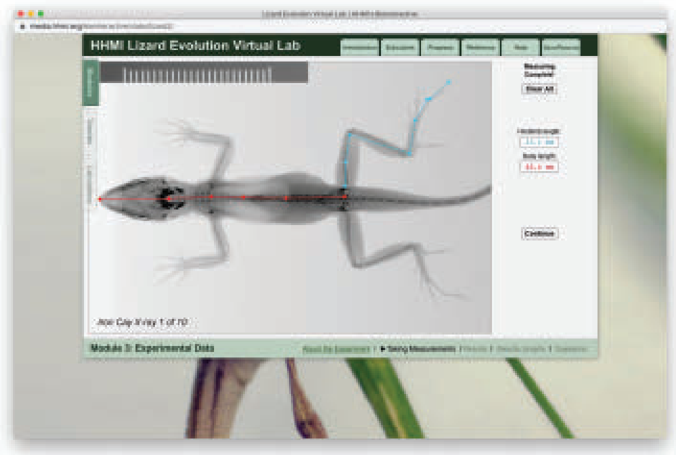

Figure 1. Screenshot from the Lizard Evolution Virtual Lab showing how users measure phenotypes in anole X-rays.

whether or not the lizards on the experimental islands adapted. Measuring, data analysis, and guided mathematical calculations reinforce scientific reasoning and help teachers to learn and integrate these science practices.

Direct links to related student activities or resources. To help teachers link their learning about evolutionary concepts with resources and activities to use with their students, teachers use some of the same interactives as students. One example is the interactive tool EarthViewer, which is an application that allows learners to navigate, visualize, and learn about the changes in Earth's long geological history (Figure 2). Numerous factors can be traced across time, including atmospheric composition, global temperature, biodiversity, day length, solar luminosity, and the location of modern-day cities. Optional links to other related BioInteractive materials are provided at the bottom of each course page; in this case EarthViewer is linked to an additional resource, "Making of Mass Extinctions."

End of lesson review quizzes and end of unit test. Research suggests that frequent assessments improve learning and retention of content (Roediger & Karpicke, 2006). To help provide formative and summative feedback, at the end of each lesson

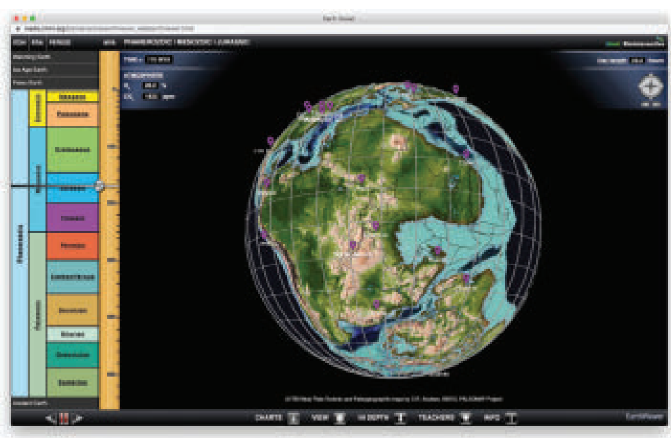

Figure 2. BioInteractive's EarthViewer, featuring the Paleo Earth timeline on the left (with other timelines available).

teachers respond to 4–7 review questions, and at the end of the unit they complete a 15-question test. Teachers need to receive at least an 80% on an assessment to proceed to the next lesson or unit in the certificate version of the course.

Deeper Content Dives. Deeper Content Dives are offered to further investigate and strengthen teachers' knowledge in the subject matter explored within the particular lesson. When investigating the origin of genetic variation for inherited traits, a link to a Deeper Content Dive leads to a video describing how color vision evolved in the lineage that led to modern humans (Figure 3).

Educator Tips. Similar to the Deeper Content Dives, Educator Tips are additional resources to provide teachers with implementation tips for BioInteractive activities. These are created by educators showcasing how they use the resources within their own classrooms. The majority of Educator Tips also include videos with the educator and visual aids to explain how they use the resource. These also include links to the resource and associated worksheets, instructions, and additional information so that educators can easily implement the content in their classroom.

Certificate or noncertificate version. The BioInteractive survey at NSTA in 2015 suggested that some teachers wanted to take an online course to help them meet requirements for PD hours. To accommodate those needs, a certificate version of the course is available. Teachers can receive one certificate after completing Unit 1, which is estimated to require at least 10 hours. Teachers can receive another certificate after completing both Units 2 and 3, which together are estimated to require at least 5 hours. Teachers can complete the two segments independently. On the other hand, some teachers wanted to access portions of the course materials "just in time," and some wanted to use portions of the course with their own students. To accommodate those needs, a noncertificate

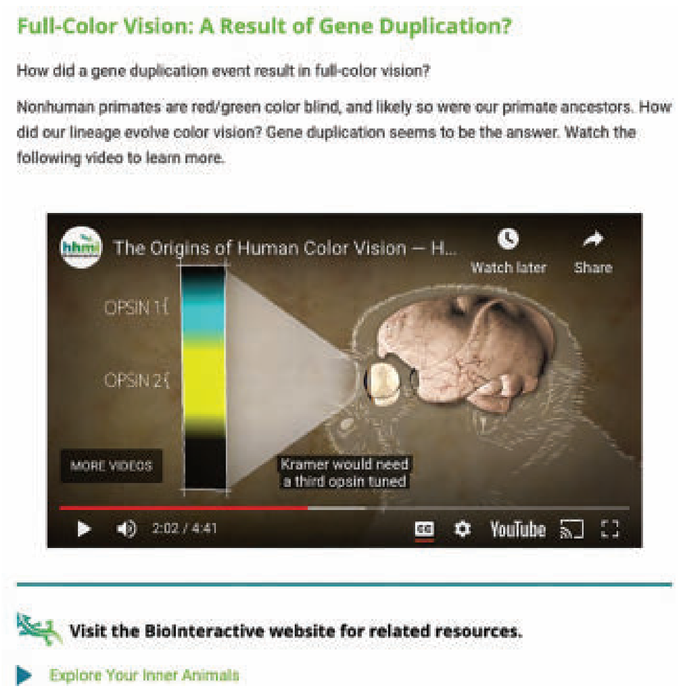

Figure 3. Screenshot of an interactive resource provided in a Deeper Content Dive regarding inheritance. Users are able to watch a video describing gene duplication in the lineage that led to humans, leading to color vision.

version of the course is available that allows teachers to access all the lessons as needed.

○ Evaluation of the Course

To gain insights into how well the course supported teachers in meeting the course learning goals and to inform revisions of the course (updated in October 2019) and the development of future BioInteractive professional learning courses, we asked teachers of the first version of the course to complete a postcourse survey after completing Unit 1 and separately after completing both Units 2 and 3. The survey included pre-post retrospective confidence questions because we wanted to better understand subjective changes experienced by course participants (Hill & Betz, 2005). In other words, we wanted to learn how teachers felt about the effectiveness of the course and how it affected their growth in knowledge and skill development. We formally tested statistical hypotheses about changes in means between teachers' self-reported confidence before and after the course using two-tailed, paired t-tests and computed Cohen's d values for each comparison of means.

The evaluated version of the course used an electronic notebook and was only available in the certificate (prescribed sequence) version. A total of 92 participants completed the survey for Unit 1, and 69 completed the survey for Units 2 and 3.

○ What We Learned

Overall, the large majority of teachers responded positively to the online course. When asked if the course met their expectations, 91% of the teachers completing Unit 1 agreed, as did 96% of the teachers completing Units 2 and 3. When asked if they planned to implement the lessons with their students, 94% of teachers completing Unit 1 said "yes" as did 91% of teachers completing Units 2 and 3. Analysis of open-ended questions in the survey suggests that teachers appreciated the embedded media, especially short video clips; the student lessons provided within the context of the PD lessons; the clarity of the evidence for evolution case studies; and the inclusion of data from actual studies. Paired-samples t-tests conducted to compare the changes in means between teachers' self-reported confidence before and after the course all showed highly significant increases in confidence ($p < 0.0001$) with medium to large effect sizes, ranging from $d = 0.60$ to 1.32. We will describe the results of the evaluation in light of the teacher learning objectives, beginning each section with representative quotes from post surveys that personify the quantitative results. Tables summarizing all the postsurvey responses from teachers completing Unit 1 and Units 2 and 3 are included in Table 1 and Supplemental Data (Tables S2–S4, online).

Goal 1: Deepen content knowledge of evolutionary concepts that are essential to NGSS and AP Biology courses.

> *"This was an unbelievable experience! I loved every bit of it. It makes the study of evolution so clear…. If teachers today taught evolution the way you did in this course … everyone would totally understand it. This was a fun course in which I felt I was a scientist actually doing the investigations and learning evolution at the same time."*

> *"This course allowed me to act and study like a scientist. This was amazing in being able to see actual evidence of organisms undergoing evolution. It really gave a clear and concise picture of what evolution is all about."*

In response to general survey questions (see Supplemental Data, Table S2, online), 95% of teachers, on average, agreed or strongly agreed that the course deepened their understanding of evolution and that the course assignments provided useful opportunities for them to strengthen their knowledge. Additionally, pre-post retrospective survey questions about teachers' confidence in their understanding of key concepts from each unit showed that there was a significant and substantial increase in the percentage of users that were moderate to highly confident. At the end of Unit 1, 94% of teachers were moderately to highly confident in their content knowledge from the unit (see Supplemental Data, Table S3), as were 97% of teachers at the end of Units 2 and 3 (see Supplemental Data, Table S4). The largest gains in confidence in Unit 1 were for calculating descriptive statistics that explain variation in populations (a learning outcome that aligns with the science practices of analyzing and interpreting data and of using mathematics, as well as standards in the Common Core), for describing the similarities and differences among four mechanisms of evolution, and for using evidence to relate the strength of selection to the rate of change in phenotypes in a population over time. After Units 2 and 3, teacher confidence in their content knowledge had the largest gains in using evidence to reconstruct phylogenetic relationships and explaining how different definitions of species affect how biologists study speciation. Again, many of the learning gains are in areas highly integrated with science practices.

Goal 2: Increase confidence and comfort in teaching evolution content to general biology and AP Biology students.

> *"This is not my field of expertise, so I am very appreciative that this course gave me a lot more confidence than I had before I took it. I also took it to find more resources for my students which I got and am looking forward to using."*

Table 1 summarizes important gains in teachers' confidence in teaching evolution both at the general high school levels and at advanced levels. The percentage of teachers that are highly confident in their ability to teach general biology increased by 30% after Unit 1 and 32% after Unit 2. Teacher's confidence in teaching evolution at an advanced college level also grew substantially, with the percentage of teachers reporting high confidence increasing by 29% after Unit 1 and after Units 2 and 3.

Goal 3: Identify major evolutionary concepts in scientific studies, authentic data, or educational media used to teach evolution.

> *"For me, this course was … about getting new ideas regarding resources, how to better sequence materials, how to ask more engaging/clear questions, and how to better collect and use data in my classroom. This course was super helpful in all of these ways, and I really appreciate having free and excellent PD in this area."*

The success of this goal can best be seen in Table 1, in which the percentage of teachers reporting moderate to high confidence in their ability to utilize authentic scientific data was 90% after Unit 1 (an increase of 46% compared to their confidence before the course) and 96% after Units 2 and 3 (an increase of 33%).

Table 1. Summary and analysis of teacher overall pre-post retrospective confidence by units. The mean was derived by converting the Likert scale into numerical values (1 = no confidence, 2 = slight confidence, 3 = moderate confidence, and 4 = high confidence).

General Confidence Questions			No Confidence %	Slight %	Moderate %	High %	Mean	Std. Dev	Cohen's *d*
Teaching evolution to regular high school biology students	Unit 1	Pre	3.3	12.0	37.0	47.8	3.29	0.81	0.60
		Post	1.1	4.3	16.3	78.3	3.72	0.60	
	Units 2 & 3	Pre	2.9	10.1	37.7	49.3	3.33	0.78	0.69
		Post	0.0	2.9	15.9	81.2	3.78	0.48	
Teaching evolution at an advanced level (e.g., AP Biology)	Unit 1	Pre	9.8	26.1	43.5	20.7	2.75	0.90	0.72
		Post	5.4	3.3	41.3	50.0	3.36	0.79	
	Units 2 & 3	Pre	7.2	20.3	47.8	24.6	2.90	0.86	0.68
		Post	1.4	7.2	37.7	53.6	3.43	0.70	
Assigning authentic scientific data to students to support learning objectives in evolution	Unit 1	Pre	7.6	47.8	35.9	8.7	2.46	0.76	1.32
		Post	1.1	7.6	40.2	51.1	3.41	0.68	
	Units 2 & 3	Pre	5.8	31.9	44.9	17.4	2.74	0.82	1.04
		Post	0.0	4.3	43.5	52.2	3.48	0.58	
Using HHMI BioInteractive resources with students to scaffold scientific practices	Unit 1	Pre	17.4	41.3	28.3	13.0	2.37	0.92	1.13
		Post	1.1	10.9	44.6	43.5	3.30	0.71	
	Units 2 & 3	Pre	11.6	34.8	42.0	11.6	2.54	0.85	1.23
		Post	0.0	5.8	43.5	50.7	3.45	0.61	
Using HHMI BioInteractive resources to teach students evolution content	Unit 1	Pre	12.0	28.3	46.7	13.0	2.61	0.86	1.18
		Post	1.1	5.4	34.8	58.7	3.51	0.65	
	Units 2 & 3	Pre	8.7	27.5	50.7	13.0	2.68	0.81	1.31
		Post	0.0	2.9	34.8	62.3	3.59	0.55	

Goal 4: Identify and incorporate relevant BioInteractive resources to illustrate evolutionary content and science practices in teachers' own course(s).

> *"I hoped to learn new material and get new ways to teach my students and I got exactly that. I was hoping to be inspired to try some new things in the classroom and I was!!"*

> *"This was totally amazing. This helped me see how I can get my students involved in acting like a scientist by using real world applications without having to go to the Galapagos Islands, etc. I was totally engaged and excited throughout this entire course. I can't wait to show my students these great activities."*

Nearly all teachers (96%) agreed or strongly agreed that they were introduced to instructional resources from HHMI BioInteractive and plan to integrate these resources into the classroom. Additionally, Table 1 shows significant increases in educator's confidence in utilizing BioInteractive resources to scaffold scientific practices and to teach students evolution content. For scaffolding science practices, the percentage that reported moderate to high confidence increased from 41% to 88% after Unit 1 and from 54% to 94% after Units 2 and 3. Similarly, for using BioInteractive resources to teach students evolution content, the percentages reporting moderate to high confidence increased from 59% to 94% of teachers for Unit 1 and from 64% to 97% for Units 2 and 3.

○ Changes to the Course Based on the Evaluation

Time Estimates

A beta version of the course was piloted with six teachers who completed all three units. Results from the pilot test led to the removal of some content and was the basis for an initial estimate of the time needed to complete each unit which was initially five hours for Unit 1 and five hours for both Units 2 and 3. However, among the pilot teachers there was wide variation in the time commitment needed for the course. Analysis of open-ended feedback from some teachers in the evaluation suggested they needed more time for Unit 1 and we increased the estimated time for Unit 1 to 10 hours.

Notebook

In the initial launch of the course, we included an electronic notebook that participants used to answer reflection and extension questions on the course content and teaching the content to students.

For longer assignments with many graphics, they downloaded and completed individual journal worksheets. Feedback from the evaluation suggested that these options were cumbersome, so in the updated version of the course, we combined the notebook and worksheets into a single comprehensive workbook for each unit available as fillable PDFs. Follow-up discussions with participants suggested the fillable PDFs were easier to develop than the original artifact-collection method and was easier to use.

○ Comparison to Other Research on Online Professional Development

Research on online PD is developing, though more studies are needed to cover this growing area and its diversity of formats. Similar to the results of the evaluation of our course, other researchers have found that many teachers generally have positive experiences with online PD (e.g., Parsons et al. 2019, Yoon et al., 2020). Surveys and evaluations suggest teachers prefer online PD, especially if it is not required, because it is more convenient than other forms of PD; the materials are accessible anytime, including "just in time"; they can apply what they learn to their own practice; and it is noncompetitive, which supports stronger learning environments (Nelson, 2019). Some rigorously designed studies suggest that online PD can be just as effective or even more effective than more expensive face-to-face PD (e.g., Fishman et al., 2013; Kissau, 2015; Yoon et al., 2020), from teachers' perceptions of their learning and studies on student learning. This work is important because online PD affords the scale needed to impact a nation of teachers.

○ Summary

We recognize that teachers are the most important investment for increasing students' understanding of evolution and the science practices that serve as the basis for generating and interpreting the evidence for this overarching framework for biology. So far, over 2200 learners have engaged with the course. Our hope is that the BioInteractive Online Professional Learning: Evolution course continues to grow teachers' confidence in understanding and teaching evolution and provides useful resources to make their lives easier and help student learn these vital concepts. We welcome feedback to continue to improve the online PD course and for future offerings.

Acknowledgments

Dr. Marjee Chmiel at HHMI designed the evaluation survey, conducted a pilot test of a beta version of the course, and provided valuable insights into the course design. Moodle technical course design at Education Development Center (EDC) was completed by Nevin Katz, Valerie Weagle, Kirsten Peterson, Anne Curione, Jesse Campbell, Moya Hynes, Teo Vitkauska, and Clare Crawford. Dr. Ellie Rice curated the HHMI evolution resources and created an initial framework for the content of the course. Dr. Laura Bonetta at HHMI conceived the project and provided valuable discussions and reviews of the course. Thanks to the pilot teachers who provided valuable feedback on a beta version of the course, and the teachers who completed the course and filled out the post course survey. Thanks to the anonymous reviewers for making suggestions that improved the manuscript.

References

Desimone, L.M. (2009). Improving impact studies of teachers' professional development: toward better conceptualizations and measures. *Educational Researcher*, *38*(3), 181–99.

Fishman, B., Konstantopoulos, S., Kubitskey, B.W., Vath, R., Park, G., Johnson, H. & Edelson, D.C. (2013). Comparing the impact of online and face-to-face professional development in the context of curriculum implementation. *Journal of Teacher Education*, *64*(5), 426–38.

Friedrichsen, P.J., Linke, N. & Barnett, E. (2016). Biology teachers' professional development needs for teaching evolution. *Science Educator*, *25*(1), 51–61.

Griffith, J.A. & Brem S.K. (2004). Teaching evolutionary biology: pressures, stress, and coping. *Journal of Research in Science Teaching*, *41*(8), 791–809.

Ha, M., Baldwin, B.C. & Nehm, R.H. (2015). The long-term impacts of short-term professional development: science teachers and evolution. *Evolution Education and Outreach, 8*(1), 11.

Hawley, P.H. & Sinatra, G.M. (2019). Declawing the dinosaurs in the science classroom: reducing Christian teachers' anxiety and increasing their efficacy for teaching evolution. *Journal of Research in Science Teaching*, *56*, 375–401.

Hill, L.G. & Betz, D.L. (2005). Revisiting the retrospective pretest. *American Journal of Evaluation*, *26*(4), 501–17.

Hord, S. (2004). *Learning Together, Leading Together: Changing Schools through Professional Learning Communities.* New York: Teachers College Press.

Johnson, W.R. & Lark, A. (2018). Evolution in action in the classroom: engaging students in science practices to investigate and explain evolution by natural selection. *American Biology Teacher*, *80*(2), 92–99.

Kim, S.Y. & Nehm, R.H. (2011). A cross cultural comparison of Korean and American science teachers' views of evolution and the nature of science. *International Journal of Science Education, 33*(2), 197–227.

Kissau, S. (2015). Type of instructional delivery and second language teacher candidate performance: Online versus face-to-face. *Computer Assisted Language Learning*, *28*(6), 513–31.

Luft, J., Ortegaz, I. & Wong-Kavas, S. (2009). NSTA's state of science education survey.

Nehm, R. H., Kim, S. Y., & Sheppard, K. (2009). Academic preparation in biology and advocacy for teaching evolution: biology versus non biology teachers. *Science Education, 93*(6), 1122–46.

Nelson, J. & Bohanon, H. (2019). Blue ocean shift: evidence-based practice in the professional development of teachers. *Journal of Advanced Corporate Learning*, *2*, 4–20.

Nunez, E.E., Pringle, R.M. & Showalter, K.T. (2012). Evolution in the Caribbean classroom: a critical analysis of the role of biology teachers and science standards in shaping evolution instruction in Belize. *International Journal of Science Education*, *34*(15), 2421–53.

Parsons, S.A., Hutchison, A.C., Hall, L.A., Parsons, A.W., Ives, S.T. & Leggett, A.B. (2019). U.S. teachers' perceptions of online professional development. *Teaching and Teacher Education*, *82*(1), 33–42.

Plutzer, E., Branch, G. & Reid, A. (2020). Teaching evolution in U.S. public schools: a continuing challenge. *Evolution: Education and Outreach*, *13*(1), 1–15.

Roediger, H.L. & Karpicke, J.D. (2006). Test-enhanced learning. *Psychological Science, 17*(3), 249–55.

Sanders M. & Ngxola N. (2009). Addressing teachers' concerns about teaching evolution. *Journal of Biological Education*, *43*(3), 121–28.

Sickel, A.J. & Friedrichsen, P. (2013). Examining the evolution education literature with a focus on teachers: major findings, goals for teacher preparation, and directions for future research. *Evolution: Education and Outreach, 6*(1), 23.

Spillane, J.P. & Louis, K.S. (2002). School improvement processes and practices: professional learning for building instructional capacity. *Yearbook of the National Society for the Study of Education, 101*(1), 83–104.

Wilson, S.M. (2013). Professional development for science teachers. *Science, 340* (6130), 310–13.

Yoon, S.A., Miller, K. & Richman, T. (2020). Comparative study of high-quality professional development for high school biology in a face-to-face versus online delivery mode. *Educational Technology & Society*, *23*(3), 68–80.

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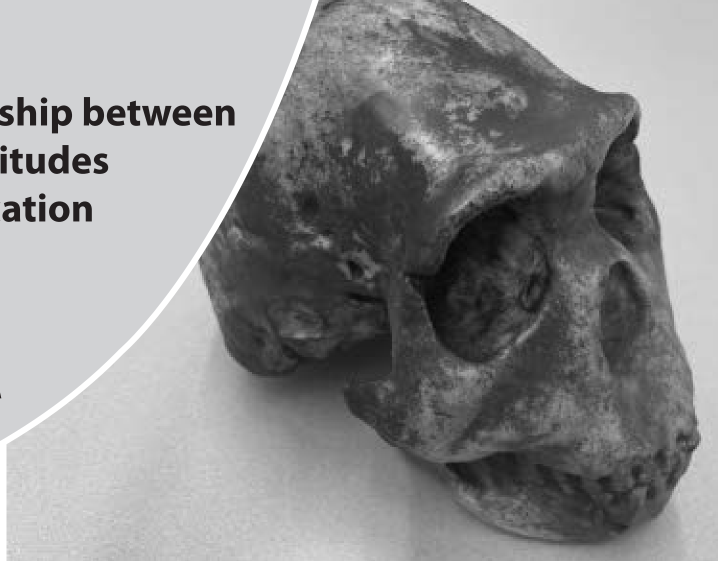
RESEARCH ON LEARNING

Exploring the Relationship between Science, Religion & Attitudes toward Evolution Education



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Abstract

While some have argued that abandoning religious belief is the only way to help religious individuals accept evolution, we strongly contend that highlighting faith-evolution compatibility is much more effective. This article describes a professional development event for science teachers and religious educators highlighting ways to teach human evolution using a science inquiry approach coupled with methods for helping students reconcile science and religion. Since many science teachers in our population face a highly religious student body, are religious themselves, and have religious education integrated into the school system, we asked them to invite the religious educators (i.e., seminary teachers) at their schools to join them at the event. In addition, a group of religious educator faculty members from the local university joined the event. We collected data both before and after intervention. Results showed that the event strengthened understanding of the intersection between evolution and religion for this particular faith group, decreased feelings of conflict in participants themselves, and increased their confidence and comfort level in offering reconciliation to students and designing lesson plans that include human examples of evolution. Differential impacts on each group of participants are discussed in terms of what we can apply to efforts like this going forward.

Key Words: *evolution education; reconciliation; ReCCEE; professional development workshop.*

○ Introduction

High school teacher beliefs affect how many students are taught evolution in their biology classrooms. According to the National Survey of High School Biology Teachers, which surveyed 926 public high school biology instructors across the nation, 13% of the teachers actively advocate creationism or intelligent design in their classroom for at least one hour of class time. Meanwhile, 28% of teachers advocate for evolutionary biology in their classroom, and the remaining 60% of teachers neither advocate for creationism nor evolutionary biology (Berkman & Plutzer, 2011). Research also shows that teachers who view evolution positively are more likely to cover standards- and nonstandards-based evolutionary topics compared to colleagues who do not view evolution positively (Borgerding, 2012).

Recent research has been conducted to draw conclusions about why so many teachers are not teaching evolution in their classrooms. Confidence may be a significant factor. The *Report of the 2018 NSSME+* found that only 63% of high school biology / life science teachers considered themselves very well prepared to teach evolution (Banilower et al., 2018). These teachers listed evolution as the topic they had the least confidence to teach compared to all other topics listed. Along with confidence, many teachers do not teach evolution because it is not in their curriculum or they want to avoid conflict (Hermann et al., 2020). With that said, some teachers may perceive potential conflict among parents or students but in reality may never encounter such problems, depending on the community in which they live (Hermann, 2013). These barriers impede evolution education in high school biology classrooms.

Focusing on the nature of science (NOS) is a commonly used and proven approach to gaining acceptance when teaching evolution. Studies with high school biology teachers reveal significant relationships between an understanding of NOS and the acceptance of evolutionary theory (Akyol et al., 2010; Rutledge & Warden, 2000). Especially for religious individuals, an understanding of the differences between the purposes of science and religion can have a large impact (Cavallo & McCall, 2008; Cofré et al., 2017; Dunk et al., 2017). Understanding NOS is an excellent way to reduce feelings of tension between religion and science, and we believe it is an excellent starting point for teaching evolution.

One common approach to teaching evolution, however, assumes that students do not accept evolution because of a deficit in knowledge on the subject. This approach focuses on teaching the facts of evolution, assuming a correlation between knowledge and acceptance. Studies on the efficacy of teaching the facts as a means of increasing acceptance of evolutionary theory, in the absence of additional strategies, have yielded varying results. A series of more recent studies have suggested a well-supported, positive relationship between knowledge of evolution and its acceptance (Dunk et al., 2017; Glaze et al., 2014; Rissler et al., 2014; Weisberg et al., 2018). However, a portion of the literature has found no correlation (e.g., Bishop & Anderson, 1990;

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Brem et al., 2003; Chinsamy & Plagányi, 2008; Mead et al., 2017; Nehm & Schonfeld, 2007; Sinatra et al., 2003). Taken to an extreme, this approach may assume those who do not accept evolution are of lower intelligence or reasoning ability (e.g., Honey, 2015; Lawson & Weser, 1990). In this extreme approach, unproven claims and inflammatory statements imply that a rejection of evolution is the result of lower cognitive aptitude and unintelligence. Unsurprisingly, we have found this mindset to be polarizing and unhelpful in changing attitudes toward acceptance of evolution.

While methods of research and subsequent opinions differ, it is reasonable to assume that one's level of knowledge plays some role in evolution acceptance. However, the relationship between knowledge and acceptance appears to be influenced by a number of external factors aside from understanding. These factors include religious beliefs and backgrounds (Dagher & BouJaoude, 1997; Deniz et al., 2008; Miller, 2006) as well as views about the nature of religion and pressure from parents (Winslow et al., 2011). In fact, with Judeo-Christian religions, several studies agree that those who hold a literal interpretation of the Bible are more likely to reject evolution (Baker, 2013; Berkman & Plutzer, 2010; Hill, 2014). For many religious people, learning the facts about evolution will not be enough for them to accept. Many may still see the theory of evolution as threatening to their religion. Additional interventions are often necessary for these students. We acknowledge, however, that not all religious faiths find conflict with evolution, and thus, religious beliefs likely play no role in the acceptance of evolution.

Religious Cultural Competence in Evolution Education (ReCCEE) appears to be a useful framework to overcome existing potential religious barriers to learning evolution (Barnes & Brownell, 2017). Data suggests that students facing an instructor with a negative disposition toward their religious beliefs have adverse experiences when learning evolution (Barnes et al., 2017). The practices of ReCCEE are aimed at helping educators "reduce students' perceived conflict between evolution and religion, increase students' acceptance of evolution, and help create more inclusive undergraduate biology classrooms" (Barnes & Brownell, 2017, p. 1). These strategies include acknowledging the potential conflict, exploring diverse views on evolution and religion, teaching about the nature of science and the nature of religion, outlining diverse viewpoints about the ways in which science and religion can coexist, introducing role models who accept evolution and maintain faith, and discussing potential compatibility. These practices are shown to be effective at bridging the gap between evolution education and orthodox religious belief in even just six minutes of instruction (e.g., Truong et al., 2018).

While considerable efforts have been made to help students and faculty accept evolution for themselves, there have been far fewer strides toward equipping teachers with the necessary knowledge and tools to effectively teach evolution, especially to their religious students whose religious beliefs may present conflict (e.g., many Judeo-Christian traditions). The primary vehicle for change in this area has been top-down administrative changes. Judicial courts have repeatedly supported the teaching of evolution over intelligent design (e.g., *Edwards v. Aguillard*, 1987; *Kitzmiller v. Dover Area School District*, 2005; *Peloza v. Capistrano Unified School District*, 1992), and state standards typically require evolution education (Lerner, 2000). However, while judicial and political support for evolution education is essential, it is far from sufficient for engaging religious teachers and students. Wording of state standards can be filled with ambiguity, making it easy for teachers to provide cursory explanations or cast doubt on the scientific consensus regarding evolution (Lerner, 2000). Additionally, even when quality state standards are implemented effectively, such as those suggested in "A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas," students can only be required to know, understand, and apply evolutionary concepts. Long (2012) found in his interviews of religious students that they were able to separate the facts of evolution from their religious beliefs and perform well on exams without believing the information.

There have been other interventions in the past attempting to reconcile students' religious beliefs with evolution (e.g., Lindsay et al., 2019). Pobiner and others (2018) used human evolution examples to help aid high school biology students in evolution understanding and acceptance. In addition, strategies were implemented to help create an environment that was sensitive to various religious and cultural beliefs. Results from this research show that using human examples as well as teaching evolution in a culturally and religiously sensitive environment helped students to gain both evolution understanding and acceptance.

Based on our literature review, we know that many students (and teachers) see a conflict between certain religious beliefs (especially Judeo-Christian beliefs) and science, and specifically evolution. It has also been shown that simply giving them more knowledge about evolution does not resolve the conflict. Currently, tools to help high school teachers approach religious students in faith-friendly ways, and even to navigate their own religious beliefs, are scarce. We propose that it is crucial that we facilitate communication between both those who teach biology and those who advise in religion in order to provide tools for reconciling evolution amongst religious audiences. In this study, we tested the effectiveness of a professional development workshop that brought together science in-service teachers and high school religious educators of a specific Christian denomination under the tutelage of a famous evolutionary anthropologist to learn about evolution and to help construct approaches to support students in resolving the conflict.

○ Methods

Ethics Statement

All data for this study was collected anonymously with no identifying information collected. It was also not analyzed until it had become archival data. The Institutional Review Board determined that review was not necessary (IRB2020-410).

Participants

To determine the effectiveness of our intervention on both science and religious instructors, we recruited 76 participants. Science instructors consisted of 43 secondary education in-service teachers from local junior highs and high schools in Utah County. The workshop was advertised through the local Science Teachers Association (USTA) listserv as a professional development opportunity. Secondary ed participants received 4.0 relicensure and a \$100 stipend in exchange for their participation. An additional 6 participants were preservice secondary education biology teachers currently attending the hosting university. Of those participating, 12 junior high and 22 high school teachers completed both surveys ($N_{\text{Secondary biology teachers}} = 34$).

Religious instructors included 27 participants associated with religious education, specific to the predominant religion of the area, that of the Church of Jesus Christ of Latter-day Saints (CJCLDS). Participants were recruited by email and word of mouth. These participants were also offered a \$100 stipend for their participation.

Three participants were current curriculum writers of the Seminary and Institute program of the CJCLDS. Eleven were current CJCLDS seminary instructors who teach daily seminary classes, during a "release time," to CJCLDS youth attending the junior highs and high schools in the same districts as our science teacher participants. Thirteen participants were faculty who teach religious education, church history, and ancient scripture at the hosting university and who are of the CJCLDS affiliation. Of those participating, 9 seminary instructors, 3 curriculum writers, and 11 university faculty members completed both surveys; however, the 3 curriculum writers were excluded from analysis because maintaining anonymity was difficult with their small numbers ($N_{\text{seminary teachers}} = 9$; $N_{\text{religious faculty}} = 11$).

Evolution & the Church of Jesus Christ of Latter-day Saints

The major focus of the workshop was reconciliation between evolution and the prominent religion in the area, the CJCLDS. The CJCLDS has a decidedly neutral stance on the theory of evolution, stating recently, "The Church has no official position on the theory of evolution…. Nothing has been revealed concerning evolution" ("What does the church believe," 2016, p. 41). However, the CJCLDS has had a somewhat controversial past of disagreement about evolution among prominent leadership in the church (see Evenson and Jeffery 2005 for a review) that has led many members to hold on to a false belief that the CJCLDS is decidedly against evolutionary theory. The official doctrine of the CJCLDS affirms a creation and that "God directed the creation of Adam and Eve and placed their spirits in their bodies" ("What does the church believe," 2016, p. 41).

Intervention

The purpose of the workshop was to help both science and religious educators be aware of the perceived conflict in their students and find ways to help students reconcile their religious faith with learning evolution. In addition, we aimed to teach principles of human evolution, eliminate misconceptions, and increase acceptance of evolution by the participants. The workshop had two parts: "Using a Reconciliation Approach" and "Human Evolution with Dr. John Hawks," a visiting guest speaker and codiscoverer of *Homo naledi* (e.g., Berger et al., 2015).

During Part 1, Using a Reconciliation Approach, participants were led in a discussion about the nature of science and the nature of religion. They discussed the US historical events that led to this perceived tension between evolution and faith. They also were presented with and encouraged to discuss the current research surrounding what we know about the influences of evolution acceptance. We outlined our approach after the ReCCEE guidelines (Barnes & Brownell, 2017; see Tolman et al., 2020, for a detailed description), with a particular focus on acknowledging potential conflict and discussing potential compatibility. The discussion was led by a university faculty member who specializes in the preparation of secondary education students, and is himself a secondary teacher, and several university faculty members who regularly teach undergraduate majors and nonmajors introductory biology and are also members of the CJCLDS. After the presentation, participants were encouraged to discuss with each other and to ask questions of facilitators about how to effectively implement an approach like this in both the science and religion classroom.

During Part 2, Human Evolution with Dr. John Hawks, Dr. Hawks led the group in an interactive activity utilizing skull casts of multiple hominin species. Participants were encouraged to measure features and predict relatedness, to predict what things you can deduce from skeletal remains, and to ask questions of Dr. Hawks. Dr. Hawks also led participants in a discussion about how we know what we know about hominid evolution and also what things we do not yet know. The remaining time was open for a question-and-answer session where several religiously oriented questions were brought up and discussed as a group.

Measures

Upon registering at the event, participants were given an anonymous pre-survey. The full survey can be found in the Supplemental Material with the online version of this article. The survey asked participants to indicate (1) the level of conflict they think that their students perceive between evolution and religion, (2) their own understanding of the CJCLDS stance on evolution, (3) their belief in the compatibility of evolution and their religious faith, (4) their acceptance of evolutionary theory including human evolution, (5) their confidence in helping students reconcile evolution with religious belief, and (6) their comfort and confidence in using human examples to teach evolution in an interactive way in their classrooms. Upon completion of the workshop, participants were asked to take a post-survey that asked the same questions but also for them to indicate if any change had taken place, and if so, to quantify that change (again, the full survey can be found in the Supplemental Material). Participants were asked to attach their pre-survey to their post-survey and to turn it into workshop facilitators to be entered into a drawing to win a *Homo naledi* skull replica. No identifying information was collected from participants, so they were free to be honest with their responses.

Analysis

For the purpose of analysis and to maintain anonymity of participants, all science instructors (junior high and high school) were combined to represent "science instructors." "Religious instructors" were kept as two groups: seminary instructors and religion faculty from the university. Responses on each item between pre-surveys and post-surveys were compared using nonparametric methods: Wilcoxon signed-rank tests for pre-post comparisons, Mann-Whitney U tests for comparisons between two groups, and chi-square goodness-of-fit tests for comparison of proportions. Nonparametric methods were used due to the small sample size, the ordinal nature of our data, and violation of the assumption of normality. Statistical significance was set to 0.05.

○ Results

Perceptions of Student Conflict

Participants were asked to rate the amount of conflict they believe that their students feel between evolution and their religion. On a five-point Likert scale from no conflict at all (1) to extreme conflict that inhibits learning (5), a Kruskal-Wallis test showed that the differences between groups was significant, $\chi^2(2) = 6.23$, $p = 0.04$, $\eta^2 = 0.044$. Pairwise comparisons, correcting for alpha inflation, show that seminary instructors felt significantly more student conflict than secondary biology teachers ($p = 0.04$). The difference was not significant between religious faculty and seminary teachers ($p = 0.20$) or between biology teachers and religious faculty ($p = 1.0$). Perceptions of conflict did not change in response to the workshop (p = NS).

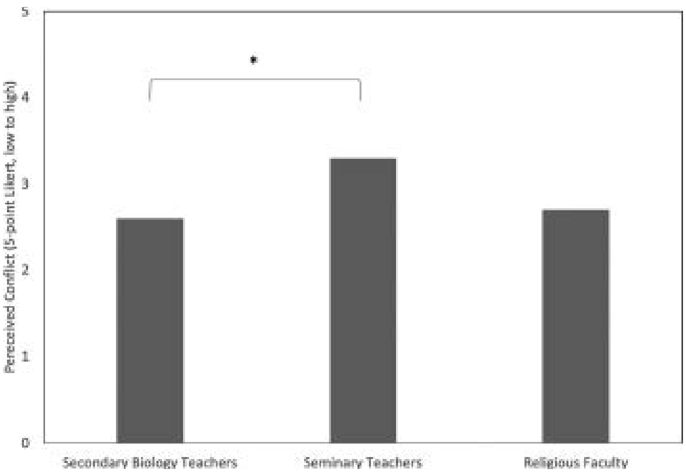

Figure 1. The conflict between evolution and religion that instructors perceived in their students. * $p < 0.05$.

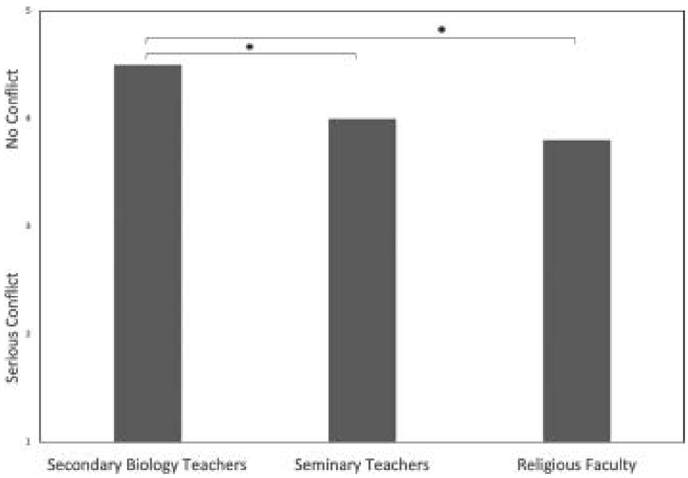

Figure 3. Perceived compatibility between religion and evolution prior to the workshop.

Understanding of Church's Stance

Participants were asked prior to and then following the workshop about their understanding of the position of the CJCLDS toward evolution (a position that is neutral). Prior to the workshop, both seminary and secondary biology teachers had a mixed understanding of the church's position, whereas all religious faculty were aware of the church's neutral position. After the workshop, secondary biology teachers made a significant shift toward a correct understanding—$\chi^2(2) = 25.12$, $p < 0.001$, $\phi = 0.86$, a large effect—although two secondary biology teachers were still unsure, or unconvinced, by the end of the workshop that the church's position is neutral (see Figure 2). Seminary teachers all ended with a correct understanding of the neutral position; however, the shift did not reach significance ($p = 0.10$).

Belief in Compatibility

Participants were asked to rank their feelings of compatibility between religious belief and evolution on a five-point scale, from low compatibility (1) to high compatibility (5). Most participants felt a high level of compatibility prior to the workshop; however, a Kruskal-Wallis test shows differences in conflict between participants—$\chi^2(2) = 6.29$, $p = 0.04$, $\eta^2 = 0.046$—with secondary biology teachers feeling the highest level of compatibility and religious faculty feeling the lowest level of compatibility (see Figure 3). No changes in perceived compatibility were seen after the workshop (p = NS).

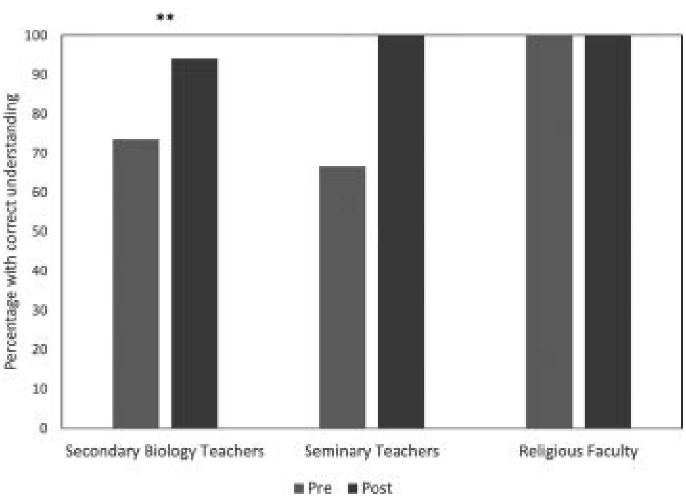

Figure 2. Understanding of the neutral position of the CJCLDS prior to and following the workshop. ** $p < 0.01$.

Acceptance of Evolution

Participants were first asked about their acceptance of organismal evolution using this prompt: "Organisms existing today are the result of the evolutionary processes that have occurred over millions of years" (from Rutledge & Sadler, 2007), on a five-point Likert scale. A Kruskal-Wallis test revealed that acceptance differed across groups—$\chi^2(2) = 6.83$, $p = 0.03$, $\eta^2 = 0.057$—with biology teachers having the highest acceptance (mean = 4.69) followed by religious faculty (mean = 4.27) and then seminary teachers (mean = 3.78). No individual pairwise comparisons were significant with a correction for alpha inflation. After the workshop, Wilcoxon signed-rank tests showed that biology teachers stayed at their same high acceptance (mean = 4.9, $p = 0.22$), seminary teachers significantly increased in acceptance (mean = 4.8, $z = 2.06$, $p = 0.04$, $r = 0.73$, a large effect), while religion faculty experienced no significant changes (mean = 4.2, $p = 0.74$).

Regarding human evolution, participants were given four options: a naturalistic viewpoint (humans evolved and God is not involved), a theistic viewpoint (humans evolved with God guiding the process), a special creation viewpoint (humans did not evolve), and no opinion. Seminary instructors had the highest proportion of special creationist ideas prior to the workshop, followed by religious faculty; no secondary biology teachers had this viewpoint (see Figure 4). By the end of the workshop, both seminary instructors and religious faculty had made shifts toward theistic evolution and away from special creationism, but the seminary teachers are the only ones that reached significance—$\chi^2(2) = 6.3$, $p = 0.04$, $r = 0.89$, a large effect.

Confidence in Helping Students Reconcile

Participants were asked to rate their confidence in helping students overcome the conflict between science and religion on a five-point

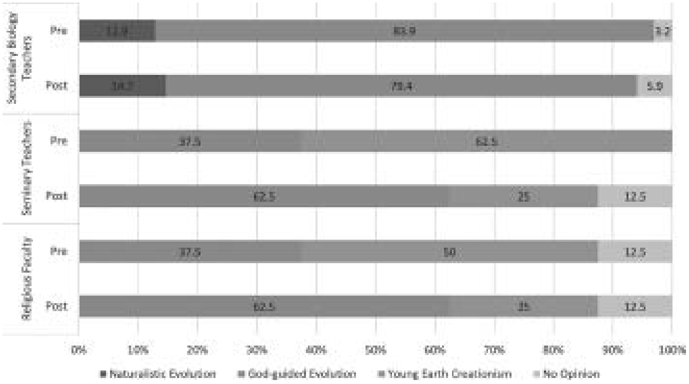

Figure 4. Viewpoints toward human evolution prior to and following the workshop. Only the change in seminary teachers reached statistical significance, $p < 0.05$.

Likert scale with 1 being low confidence to 5 being high confidence. Seminary teachers showed lower confidence both prior to and after intervention (although overall distributions were not significantly different), but all groups experienced gains in confidence, although secondary biology teachers are the only ones that reached significance, likely due to their larger sample size ($z = 2.14$, $p = 0.03$, $r = 0.37$, a medium effect; see Figure 5).

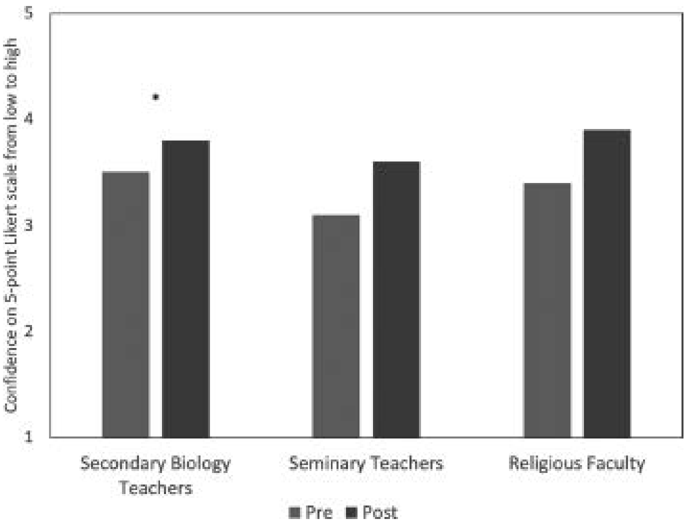

Figure 5. Participants' confidence in helping students overcome the conflict between evolution and religion prior to and following the workshop. * $p < 0.05$.

Teaching Confidence

We asked only secondary biology teachers (seminary and religious faculty left these questions blank as this is not part of their curriculum) a series of questions regarding their confidence and comfort in teaching human evolution. Teachers increased in their confidence and their comfort in using human examples to teach evolution (confidence: $z = 3.38$, $p = 0.001$, $r = 0.58$, a large effect; comfort: $z = 3.60$, $p < 0.001$, $r = 0.63$, a large effect; see Figure 6). In addition, they increased in their confidence to use new discoveries in human evolution in their curriculum ($z = 2.87$, $p = 0.004$, $r = 0.49$, a medium

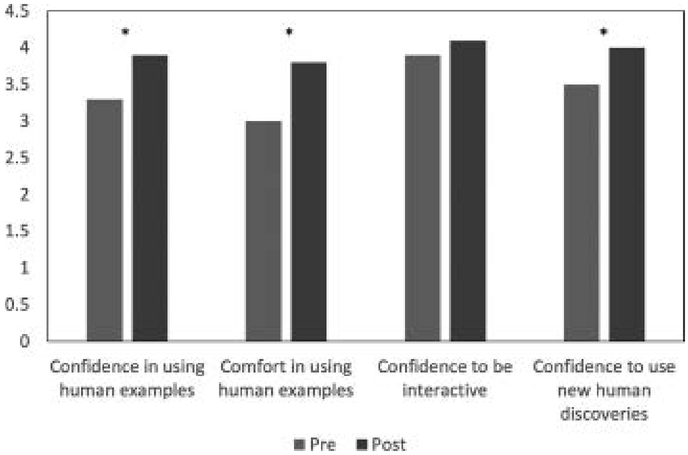

Figure 6. Confidence in teaching human evolution prior to and following the workshop as indicated by their confidence in using human examples, comfort in using human examples, confidence to use interactive lesson plans, and confidence to use new human discoveries in their curriculum. * $p < 0.05$.

effect). However, participants did not experience increases in their confidence to use interactive lesson plans; instead, they began the workshop with rather high confidence and remained high.

○ Discussion

Our results add to the body of literature demonstrating the efficacy of a ReCCEE approach. Specifically, we helped educators recognize potential conflicts and to gain tools to emphasize potential compatibility for their students. Ample evidence has shown that this approach can shift attitudes about evolutionary theory over a period of time among students in classroom settings (Barnes & Brownell, 2017; Lindsay et al., 2019, Tolman et al., 2020), and we believe it is important that both religious and science educators embrace the ReCCEE framework and gain confidence in their ability to help their students reconcile their religious faith with evolution. Specifically, encouraging both religious and science educators to acknowledge potential conflict in students when they approach this subject and then to offer students potential compatibility, or at least the space to explore this compatibility, between their religious beliefs and the science of evolution can be incredibly impactful for religious students who may see conflict with this topic. In addition, by encouraging collaboration between those teaching evolution and those teaching religion, we believe we can lessen the perceived conflict that students might encounter by equipping both kinds of educators with tools to approach the conflict, thereby making it easier for students to embrace evolution without feeling their faith is being threatened.

The secondary teachers that attended the workshop reported that their confidence to help students reconcile evolution with religion and their confidence to teach evolution increased significantly, with medium to large effect. As noted earlier, confidence may be a significant reason that teachers do not feel comfortable teaching evolution in their classroom. Sanders and Ngxola (2009) found that 49% of the 125 teachers to whom they administered questionnaires noted that they lacked knowledge to teach evolution. The knowledge they lacked was not just content knowledge but also knowledge about how to approach teaching evolution, how to respond to negative comments, and how to keep students engaged. Workshops such as ours can help teachers address these issues and also connect them with other teachers who are encountering the same issues.

It is also important to note that both seminary teachers and religious faculty were also more accepting of evolution following the workshop. Truong, Barnes, and Brownell (2018) demonstrated that a six-minute ReCCEE-based intervention was able to decrease the perceived conflict between evolution and religion in a population of undergraduate students. The shift toward greater acceptance seen in the seminary teachers and religious faculty in our sample supplies further evidence that ReCCEE-based approaches can effectively be applied outside of classrooms through short interventions. Based on the current study, we would recommend specifically that training include ways to acknowledge conflict and offer potential reconciliation. This is encouraging, as many Americans will not have the opportunity to learn about evolution in a classroom setting. We call on the biology education community to further develop applications of ReCCEE that can be taken to the public, as we believe this will be a valuable tool in combating science denialism.

These ReCCEE practices can take various forms. In the current study, we have emphasized a collaboration between science and religious educators of a particular Christian faith group (CJCLDS) to target two particular ReCCEE practices: acknowledging the existence of conflict and highlighting potential compatibility. In addition, part of Dr. Hawks' discussion focused on the nature of science and what we know and don't know about human evolution. In addition to these practices, education researchers can explore the potentials of the "Explore" ReCCEE practice, which is to encourage students to explore views on evolution and religion. Many important resources exist already to facilitate this exploration including the Clergy Letters Project (https://www.theclergyletterproject.org/), BioLogos (https://biologos.org/), the Smithsonian's Human Origins Projects' Broader Social Impacts Committee (https://humanorigins.si.edu/about/broader-social-impacts-committee), and Brigham Young University's Reconciling Evolution website (https://biology.byu.edu/reconciling-evolution/), to name a few. Each of these resources offers potential tools that educators can use within their classrooms or in a public setting to allow exploration of potential compatibility. In addition, many of these resources offer potential role models of religious figures who have embraced science or scientist or acknowledge their religious beliefs, another ReCCEE practice.

An additional ReCCEE practice is to teach the nature of science, specifically its bounds and how it differs from seeking religious truth. We would encourage researchers to explore this idea further. Additionally, outlining a spectrum of viewpoints can be effective in helping students feel less restricted to an atheistic viewpoint of evolution. Several studies have shown this to be a promising approach (e.g., Barnes, Elser & Brownell, 2017; Wiles and Alters, 2011), but more research is certainly warranted.

○ Study Limitations

While we believe this approach has great promise in increasing harmony between religious belief and the teaching of science, it is important to note that the focus of this intervention was rather specific to one particular religion (CJCLDS). However, the CJCLDS religion shares Judeo-Christian beliefs, such as the creation story and the passages found in Genesis, such that members experience many of the same conflicts regarding evolution. Additionally, our sample size was small and specific to one geographic region (western US). It would be helpful to expand such efforts to other regions that may have unique pushback against evolution (e.g., the Deep South). We have provided survey instrumentation in the Supplemental Material that can be used to assess approaches used in these other populations, although we would suggest modifying the first question to better fit the population under study and to remove or modify Question 4 concerning the specific beliefs of the CJCLDS religion. Additionally, the corresponding authors can provide additional curricular materials that may be of use in such interventions. It would also be worthwhile to track the teaching habits and student outcomes of teachers who participate in such efforts. Our results show a clear increase in educators' acceptance of evolution and confidence in their abilities to help students overcome barriers. But it is unclear how these changes may translate into actual classroom practice and subsequent student learning.

○ Conclusion

Simply providing teachers with a set of state standards regarding evolution does not necessarily prepare them to teach evolution to their religious students. It is important to note that as of 2015, over 80% of Americans consider themselves to be religious in at least some way (Pew, 2015), so it is vital that teachers have tools to reach religious students. Pobiner and others' (2018) work with the Teaching Evolution through Human Examples project is an excellent start, but resources to increase teacher confidence and effectiveness are still scarce, and involvement of religious clergy in the process is a novel idea. Our workshop not only led to increased acceptance of evolution for the individuals who participated but also impacted their perceived confidence as teachers. Members of all three groups— secondary biology teachers, seminary teachers, and religious faculty—reported feeling greater confidence in their ability to address student concerns regarding evolution. Faculty development programs specifically designed to help biology and religious instructors work together to address evolution may be a relatively simple and cost-effective way to provide teachers with the necessary tools and confidence to bridge the perceived gap between scientific and religious thought.

References

Akyol, B., Tekkaya, C. & Sungur, S. (2010). The contribution of understanding of evolutionary theory and nature of science to pre-service science teachers' acceptance of evolutionary theory. *Procedia-Social and Behavioral Sciences, 9*, 1889–93.

Baker, J.O. (2013). Acceptance of evolution and support for teaching creationism in public schools: the conditional impact of educational attainment. *Journal for the Scientific Study of Religion, 52*, 216–28.

Banilower, E.R., Smith, P.S., Malzahn, K.A., Plumley, C.L., Gordon, E.M. & Hayes, M.L. (2018). *Report of the 2018 NSSME+*. Horizon Research.

Barnes, E.M. & Brownell, S.E. (2017). A call to use cultural competence when teaching evolution to religious college students: introducing Religious Cultural Competence in Evolution Education (ReCCEE). *CBE—Life Sciences Education, 16*, es4.

Barnes, E.M., Elser, J. & Brownell, S.E. (2017). The impact of a short evolution module on students' perceived conflict between evolution and religion. *American Biology Teacher, 79*, 104–11.

Barnes, E.M., Truong, J.M. & Brownell, S.E. (2017). Experiences of Judeo-Christian students in undergraduate biology. *CBE-Life Sciences Education, 16*, ar15.

Berger, L.R., Hawks, J., de Ruiter, D.J., Churchill, S.E., Schmid, et al. (2015). *Homo naledi*, a new species of the genus *Homo* from the Dinaledi Chamber, South Africa. *Elife, 4*, e09560.

Berkman, M. & Plutzer, E. (2010). *Evolution, Creationism, and the Battle to Control America's Classrooms*. Cambridge: Cambridge University Press.

Berkman, M.B. & Plutzer, E. (2011). Defeating creationism in the courtroom, but not in the classroom. *Science, 331*, 404–405.

Bishop, B.A. & Anderson, C.W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching, 27*, 415–27.

Borgerding, L.A. (2012). Ohio High School Biology Teachers' Views of State Standard for Evolution: Impacts on Practice. *Science Educator, 21*, 19–28.

Brem, S.K., Ranney, M. & Schindel, J. (2003). Perceived consequences of evolution: college students perceive negative personal and social impact in evolutionary theory. *Science Education, 87*, 181–206.

Cavallo, A.M.L. & McCall, D. (2008). Seeing may not mean believing: examining students' understandings and beliefs in evolution. *American Biology Teacher, 70*, 522–30.

Chinsamy, A. & Plagányi, E. (2007). Accepting evolution. *Evolution, 62*, 248–54.

Cofré, H., Cuevas, E. & Becerra, B. (2017). The relationship between biology teachers' understanding of the nature of science and the understanding and acceptance of the theory of evolution. *International Journal of Science Education, 39*, 2243–60.

Dagher, Z.R. & BouJaoude, S. (1997). Scientific views and religious beliefs of college students: the case of biological evolution. *Journal of Research in Science Teaching, 34*, 429–45.

Deniz, H., Donnelly, L.A. & Yilmas, I. (2008). Exploring the factors related to acceptance of evolutionary theory among Turkish preservice biology teachers: toward a more informative conceptual ecology for biological evolution. *Journal of Research in Science Teaching, 45*, 420–43.

Dunk, R.D.P., Petto, A.J., Wiles, J.R. & Campbell, B.C. (2017). A multifactorial analysis of acceptance of evolution. *Evolution: Education & Outreach, 10*, ar4.

Edwards v. Aguillard, 482 U.S. 578 (U.S. Sup. Ct. 1987). https://supreme.justia.com/cases/federal/us/482/578.

Evenson, W.E. & Jeffery, D.E. (2005). *Mormonism and Evolution: The Authoritative LDS Statements*. Salt Lake City, UT: Greg Kofford Books.

Glaze, A.L., Goldston, M.J. & Dantzler, J. (2014). Evolution in the Southeastern USA: factors influencing acceptance and rejection in pre-service science teachers. *International Journal of Science and Mathematics Education, 13*, 1189–209.

Hermann, R.S. (2013). High school biology teachers' views on teaching evolution: implications for science teacher educators. *Journal of Science Teacher Education, 24*, 597–616.

Hermann, R.S., Shane, J.W., Meadows, L. & Binns, I.C. (2020). Understanding of evolution law among K-12 public school teachers. *American Biology Teacher, 82*, 86–92.

Hill, J.P. (2014). Rejecting evolution: the role of religion, education, and social networks. *Journal for the Scientific Study of Religion, 53*, 575–94.

Honey, P.L. (2015). Why I teach the controversy: using creationism to teach critical thinking. *Frontiers in Psychology, 6*, 793.

Kitzmiller v. Dover Area School Dist., 400 F. Supp. 2d 707 (M.D. Pa. 2005). https://law.justia.com/cases/federal/district-courts/FSupp2/400/707/2414073.

Lawson, A.E. & Weser, J. (1990). The rejection of nonscientific beliefs about life: effects of instruction and reasoning skills. *Journal of Research in Science Teaching, 27*, 589–606.

Lerner, L.S. (2000). *Good Science, Bad Science: Teaching Evolution in the States*. Washington, DC: Thomas B. Fordham Foundation.

Lindsay, J., Arok, A., Bybee, S.M., Cho, W., Cordero, A.M., et al. (2019). Using a reconciliation module leads to large gains in evolution acceptance. *CBE-Life Sciences Education, 18*. https://doi.org/10.1187/cbe.19-04-0080.

Long, D.E. (2012). The politics of teaching evolution, science education standards, and being a creationist. *Journal of Research in Science Teaching, 49*, 122–39.

Mead, R., Hejmadi, M. & Hurst, L.D. (2017). Teaching genetics prior to teaching evolution improves evolution understanding but not acceptance. *PLOS Biology, 15*, e2002255.

Miller, J.D. (2006). Science communication: Public acceptance of evolution. *Science, 313*, 765–66.

Nehm, R.H. & Schonfeld, I.S. (2007). Does increasing biology teacher knowledge of evolution and the nature of science lead to greater preference for the teaching of evolution in schools? *Journal of Science Teacher Education, 18*, 699–723.

Peloza v. Capistrano Unified School Dist., 782 F. Supp. 1412 (C.D. Cal. 1992). https://law.justia.com/cases/federal/district-courts/FSupp/782/1412/2185854.

Pew Research Center. (2015). Evolution and perceptions of scientific consensus. In *Americans, Politics and Science Issues* (pp. 88–104). Pew Research Center. https://www.pewresearch.org/science/2015/07/01/chapter-4-evolution-and-perceptions-of-scientific-consensus.

Pobiner, B., Beardsley, P.M., Bertka, C.M. & Watson, W.A. (2018). Using human case studies to teach evolution in high school AP Biology classrooms. *Evolution: Education & Outreach, 11*, ar3.

Rissler, L.J., Duncan, S.I. & Caruso, N.M. (2014). The relative importance of religion and education on university students' views of evolution in the Deep South and state science standards across the United States. *Evolution: Education & Outreach, 7*, ar24.

Rutledge, M.L., & Sadler, K.C. (2007). Reliability of the measure of acceptance of the theory of evolution (MATE) instrument with university students. *American Biology Teacher*, *69*, 332–35.

Rutledge, M.L. & Warden, M.A. (2000). Evolutionary theory, the nature of science and high school biology teachers: critical relationships. *American Biology Teacher, 62*, 23–31.

Sanders, M. & Ngxola, N. (2009). Addressing teachers' concerns about teaching evolution. *Journal of Biological Education, 43*, 121–28.

Sinatra, G.M., Southerland, S.A., McConaughy, F. & Demastes, J.W. (2003). Intentions and beliefs in students' understanding and acceptance of biological evolution. *Journal of Research in Science Teaching, 40*, 510–28.

Tolman, E.R., Ferguson, D.G., Mann, M., Cordero, A.M. & Jensen, J.L. (2020). Reconciling evolution: evidence from a biology and theology course. *Evolution: Education & Outreach, 13*, ar19.

Truong, J.M., Barnes, M.E. & Brownell, S. (2018). Can six minutes of culturally competent evolution education reduce students' level of perceived conflict between evolution and religion? *American Biology Teacher, 80*, 106–15.

Weisberg, D.S., Landrum, A.R., Metz, S.E. & Weisberg, M. (2018). No missing link: knowledge predicts acceptance of evolution in the United States. *BioScience, 68*, 212–22.

What does the church believe about evolution? (2016, October). *New Era*, 41.

Wiles, J.R. & Alters, B. (2011). Effects of an educational experience incorporating an inventory of factors potentially influencing student acceptance of biological evolution. *International Journal of Science Education, 33*, 2559–85.

Winslow, M.W., Staver, J.R. & Schamann, L.C. (2011). Evolution and personal religious belief: Christian university biology-related majors' search for reconciliation. *Journal of Research in Science Teaching, 48*, 1026–49.

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INQUIRY & INVESTIGATION

Computer-Based Activity to Engage Students in Exploring Biodiversity Decline & Extinction

LUIS CAYUELA

Abstract

Understanding the main causes of biodiversity decline is an essential part of the syllabus of any university-level course in conservation biology. A novel computer-based activity is described for introducing students to using the International Union for Conservation of Nature (IUCN) Red List database. The specific objectives of this activity are (1) to understand the main causes that threaten species worldwide and, if these causes differ, to try to elucidate the underlying processes that might be responsible for these differences in a given country and (2) to train students how to use digital biological data platforms, such as the IUCN Red List, and how to analyze and interpret biological data. To achieve these goals, students must obtain information from the IUCN Red List to assess why species are threatened globally and in a given country. Based on the total number of threatened species, students calculate the percentage of species affected by each threat within each Red List category and for all categories combined both globally and at the national level. The activity ends with a discussion in the classroom where the students are expected to share their interpretations about the main causes that threaten biodiversity at different scales of analysis and the applications of their findings in a conservation context. The activity is expected to increase the awareness of students regarding environmental issues and to develop different key competencies and basic skills as learning outcomes, including expertise in biological diagnosis, information management, and using the internet as an information source.

Key Words: *conservation biology; International Union for Conservation of Nature; threatened species; university student.*

○ Introduction

Understanding what drives species extinction is a central goal of conservation biology (Purvis et al., 2000). The *extinction* of *species* is closely tied to the *process* of natural selection, and thus it is a major component of progressive *evolution (Raup, 1994)*. However, over the past few centuries, human activities such as habitat destruction, overharvesting, introductions of invasive species, the release of toxic pollutants, and climate change have accelerated this process (Ehrlich and Ehrlich, 1981; Hughes et al., 1997; Vitousek et al., 1997). As a result, the extinction rate caused by human activities is now thousands of times higher than the expected background rate (Ceballos et al., 2010). However, many location-dependent factors that simultaneously threaten species can vary among locations on the planet and at different scales. Uncovering the underlying threats and processes that determine current species declines could improve our predictions of future declines and facilitate subsequent conservation efforts (Purvis et al., 2000).

Studying the main threats to biodiversity is an essential part of the syllabus of any university course in conservation biology, and it could also be included in general biology courses at university or high school levels. The International Union for Conservation of Nature (IUCN) Red List of Threatened Species provides reasonably standardized estimates of the global extinction risk under past and recent conditions (Mace et al., 2008), which can be used to analyze the major threats to biodiversity. The IUCN operates in the fields of nature conservation and the sustainable use of natural resources. The IUCN is involved in data collection and analysis, research, field projects, advocacy, and education. The aims of the IUCN are to influence, encourage, and assist societies around the world in order to conserve nature and to ensure the equitable and ecologically sustainable utilization of natural resources. The IUCN has observer and consultative status at the United Nations and it plays key roles in the implementation of international conventions on nature conservation and biodiversity, although it is best known to the general public for compiling and publishing the IUCN Red List of Threatened Species, which provides assessments of the conservation status of species throughout the world.

In this article, I describe a computer-based activity for introducing university level students to the main threats to biodiversity at global and regional scales by using the IUCN Red List. This activity aims to develop different key competencies and basic skills as learning outcomes, including expertise in biological diagnosis, information management, and using the internet as an information source. The specific objectives of this activity are (1) to understand the main threats to species worldwide and to elucidate the specific underlying processes that might be responsible for any differences in a given country and (2) to provide students with training

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in the use of digital biological data platforms, such as the IUCN Red List (Table 1 provides a more comprehensive list of biological databases), and the analysis and interpretation of biological data. This activity was developed to increase the awareness of students regarding environmental issues and to encourage them to explore the causes of biodiversity decline, which aligns tightly with United Nations Sustainable Development Goal SDG15 (to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss).

○ Description of the Activity

The proposed activity is intended for senior high school and college biology classes. High school students with some basic biology background might also benefit from this activity because studies of invasive species, human interaction, and environmental changes are specifically included in the Advanced Placement Biology assessment. The activity can last from two to three hours, and it should ideally be complemented with a prior theoretical session (one to two hours) explaining in more depth the main threats to biodiversity (e.g., deforestation rates in different biomes and their impacts on species loss). The activity must be conducted in a computer room with no more than 20 to 30 students to allow closer interaction between the instructor and students to facilitate discussion and debate. If necessary, the activity can also be performed independently by students as homework or taught virtually as distance education provided that they are given a step-by-step tutorial about how to proceed (see Supplemental Material Appendix 1, available with the online version of this article).

The IUCN Red List of Threatened Species is continually expanded and updated, and the number of threatened species grows each year. In the IUCN Red List, species are classified according to nine categories (IUCN Standards and Petitions Committee, 2019) based on criteria such as the rate of decline, population size, area of geographic distribution, and degree of population and distribution fragmentation. These categories include not evaluated (NE), data deficient (DD), least concern (LC), near threatened (NT), vulnerable (VU), endangered (EN), critically endangered (CR), extinct in the wild (EW), and extinct (EX). The threatened categories include VU, EN, and CR, whereas species at lower risk of extinction include LC and NT. In addition, for each species, the Red List provides information such as the type of system where it is usually found (terrestrial, marine, or freshwater), preferred habitat (forest, savanna, scrub, grasslands, wetlands, etc.), plants' growth forms

Table 1. Examples of worldwide biological databases used for research and teaching in biodiversity and conservation. Authoritative and comprehensive lists of species names and taxonomic or barcode databases are not included.

Database	Scope	Data Type	Data Access
AlgaeBase	Global database of information about algae, including terrestrial, marine, freshwater organisms (Guiry & Guiry, 2021)	Algae taxonomy, nomenclature, distribution information	https://www.algaebase.org
eBird	Online community of bird watchers who collect, manage & store observations in a globally accessible, unified database (Sullivan et al., 2009)	Bird distributions, abundances, habitat use, trends	https://ebird.org/explore
FishBase	Global biodiversity information system about finfish (Froese & Pauly, 2020)	Finfish taxonomy, biology, trophic ecology, life history, uses, historical data back 250 years	https://www.fishbase.in/home.htm
Encyclopedia of Life	Aggregated data about biological organisms (Parr et al., 2014); includes educational tools	Biological organism descriptions, media (images, videos, sounds, maps)	http://eol.org (API & 'taxize' R package) (Chamberlain et al., 2020)
Global Biodiversity Information Facility	Global network & data infrastructure funded by governments to provide open access to data about all types of life on Earth (Yesson et al., 2007)	For all types of species, georeferenced occurrences	https://www.gbif.org (API & 'rgbif' R package) (Chamberlain et al., 2021)
IUCN Red List of Threatened Species	Global list of species' conservation status, which can be used to inform & catalyze action for biodiversity conservation & policy change	For all types of species, conservation status, range, population size, habitat, ecology, use and/or trade, threats, conservation actions	https://www.iucnredlist.org (or the 'taxize' R package can be used to check species conservation status) (Chamberlain et al., 2020)
Ocean Biogeography Information System	Open-access data & information clearinghouse about marine biodiversity for science, conservation, and sustainable development (Grassle, 2000)	Marine organism diversity, distribution, abundance	https://mapper.obis.org

(annuals, epiphytes, parasites, lianas, trees, etc.), and threats (residential development, agriculture, pollution, climate change, etc.).

During this activity, students must obtain information from the IUCN Red List to assess why species are threatened globally and in a given country. I use Spain as a case study to illustrate the activity but the exercise can be conducted with data from other countries. Alternatively, different groups of students can investigate the main causes that threaten species in different countries, regions, or continents. The students then answer some questions based on the data collected. The activity ends with a discussion in the classroom where the students are expected to share their interpretations of the results and applications of their findings in a conservation context. A step-by-step summary of the activity is provided in Supplemental Material Appendix 1.

○ Procedure

Part 1. Assessing the Factors That Threaten Species Globally

To facilitate the compilation of data from the IUCN Red List, the instructor provides the student with an Excel spreadsheet (Supplemental Material Appendix 2) before the activity begins. To access the Red List search engine, students go to the IUCN Red List page (http://www.iucnredlist.org) and click on the Advanced icon. From the Red List Category tab on the left bar, the student selects only the VU category (Figure 1).

In the lower part of the bar, the student verifies that only the Species option is checked in INCLUDE, which ensures that assessments made at the level of subspecies, varieties, or populations will not be considered in the search. After making this selection, click on the Threats tab and a submenu is displayed with the different threats, and the number of species threatened by each factor is shown in parentheses (Figure 2).

The student then inserts these values in the Excel sheet in the Total values section in column B (VU). The IUCN threat category "Other options" is not included in the analyses because it provides little information about the causes that drive species extinction. It should be noted that the same species can be affected by several threats simultaneously, so the total number of species listed in a Red List category will not necessarily match with the total number of species obtained by considering all possible threats. Therefore, the total number of species classified under each Red List category (row 15 in the spreadsheet) is obtained from the Red List search engine when applying the first selection criteria (Figure 1).

The same procedure is performed for the other two Red List categories, i.e., endangered (EN) and critically endangered (CR), and the information obtained is inserted in the corresponding columns of the Excel spreadsheet (Total values). After collecting all the results, the totals for the three categories combined are calculated for each threat by summing each row for the total species included in the three Red List categories.

Part 2. Assessing Factors That Threaten Species at the National Level: Spain as a Case Study

This procedure is similar to the assessment of factors that threaten species globally (Part 1), but in the search criteria tab, students also select the country or countries under evaluation (Spain in this example) from the Land Regions drop-down list (Figure 3). The results obtained are inserted into the corresponding columns of the Excel spreadsheet, and the totals for the three categories combined are calculated (Appendix 3).

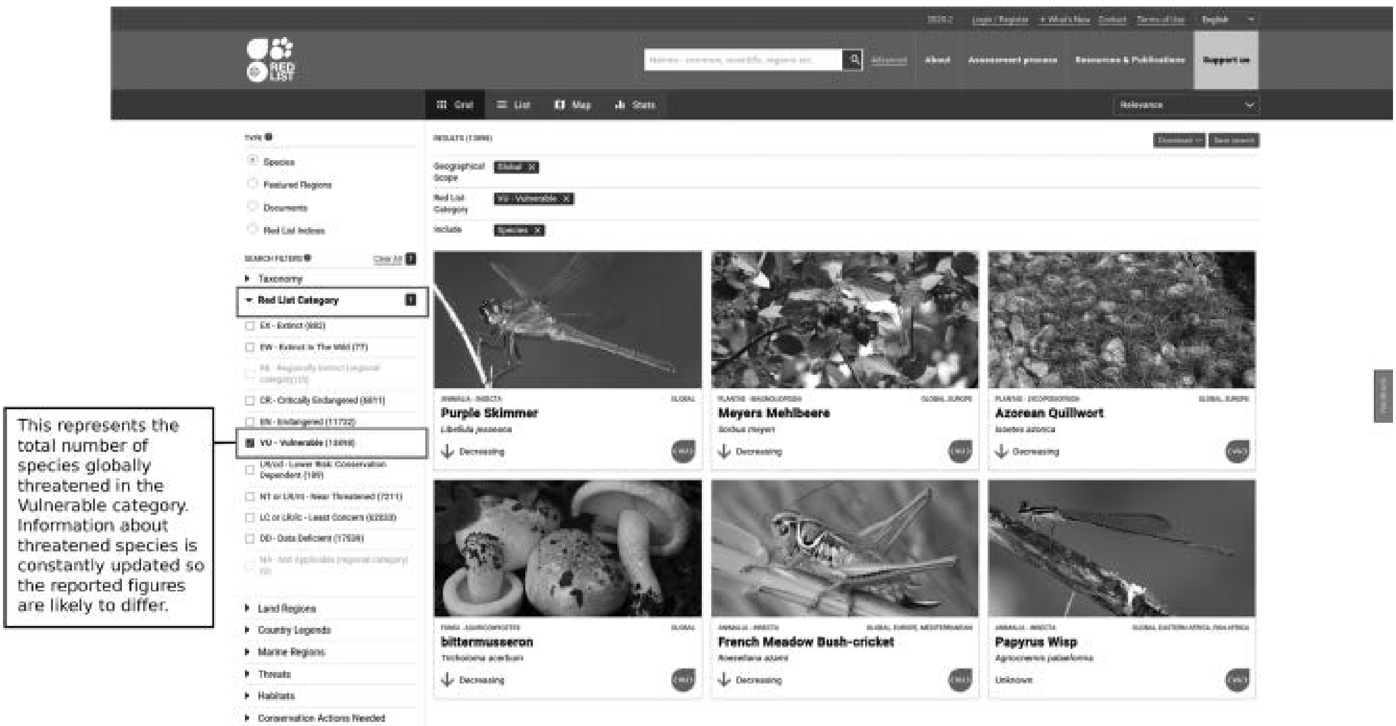

Figure 1. Display options provided by the IUCN Red List advanced search engine (left bar) for selecting species listed in one or more Red List categories.

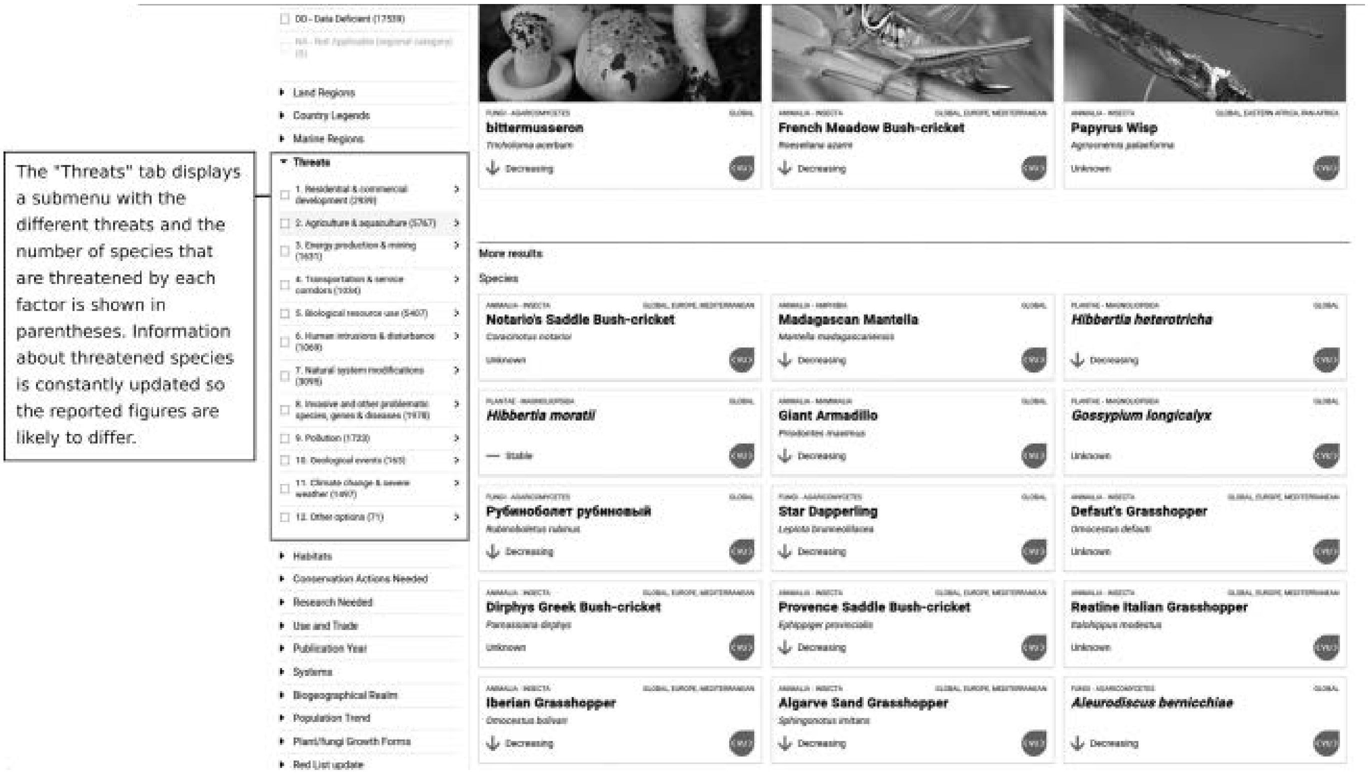

Figure 2. Display results obtained from the IUCN Red List showing the number of species under each threat listed in the vulnerable category (VU). Note, the number of species listed in each Red List category changes each time that the IUCN Red List is updated.

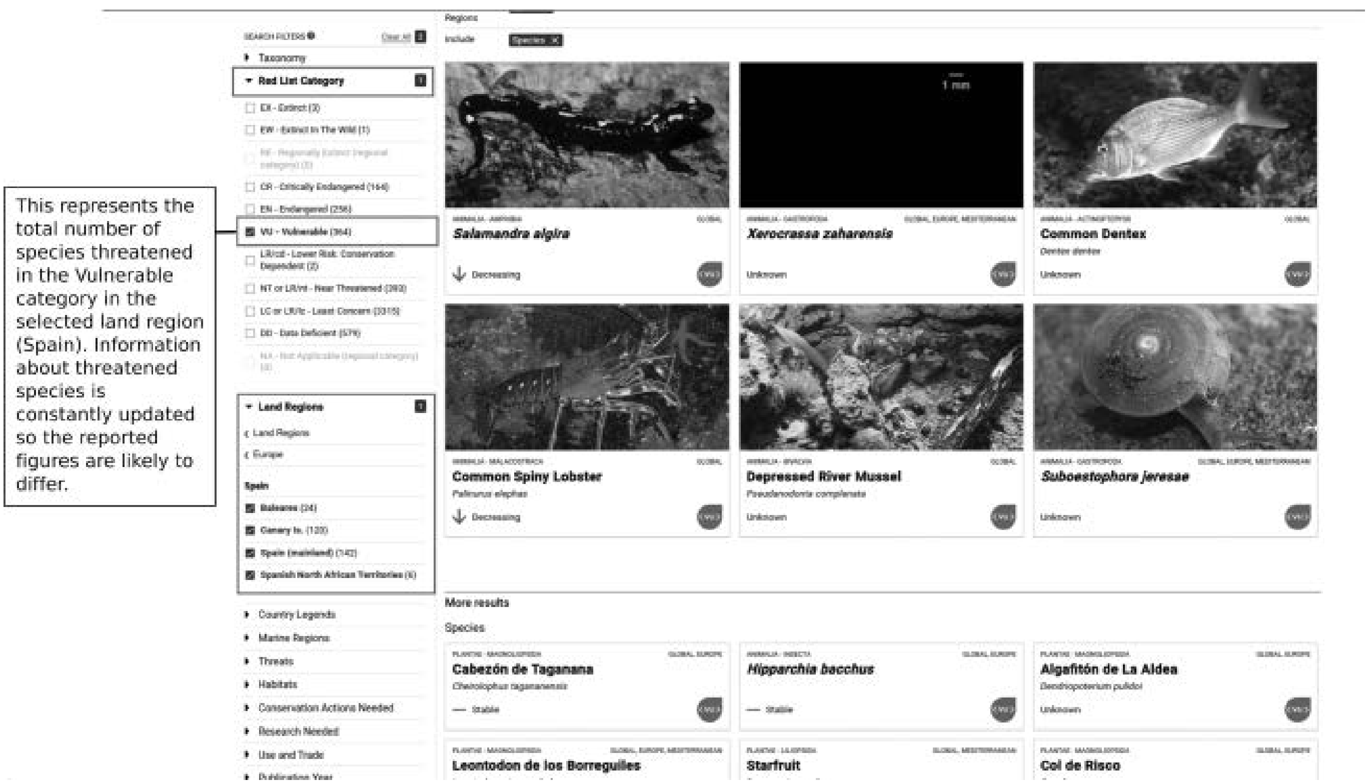

Figure 3. Display results obtained from the IUCN Red List showing the number of species under each threat listed in the vulnerable category (VU) for a particular land region, Spain in this case. Note, the number of species listed in each Red List category changes each time that the IUCN Red List is updated.

Part 3. Interpretation of Results

Based on the totals, students can calculate the percentage of species affected by each threat in each Red List category as well as for all categories combined at both the global and national levels. The procedure is repeated for the remaining Red List categories, including all categories combined.

The students then prepare a bar plot (the R code required to generate this figure is provided in Supplemental Material Appendix 4) to compare the percentage of species affected by each threat for each Red List category (including all categories combined). Only global data are used to prepare this plot (Figure 4). Similarly, students need to prepare another bar plot (the R code is provided in Appendix 4) that allows them to visually analyze whether the threats that affect species at the national level are similar to those that affect species globally (Figure 5). Only the values for all categories combined (Columns E and I) are used to produce this plot.

Part 4. Discussion Session

At the end of this activity, students are expected to address the following questions using the results obtained during the laboratory session.

1. What are the most important threats globally? Does the importance of these factors vary according to the Red List category?
2. What are the most important threats at the national level? Are there differences between the results obtained at the global and national levels? What are the main differences? What might cause these differences?

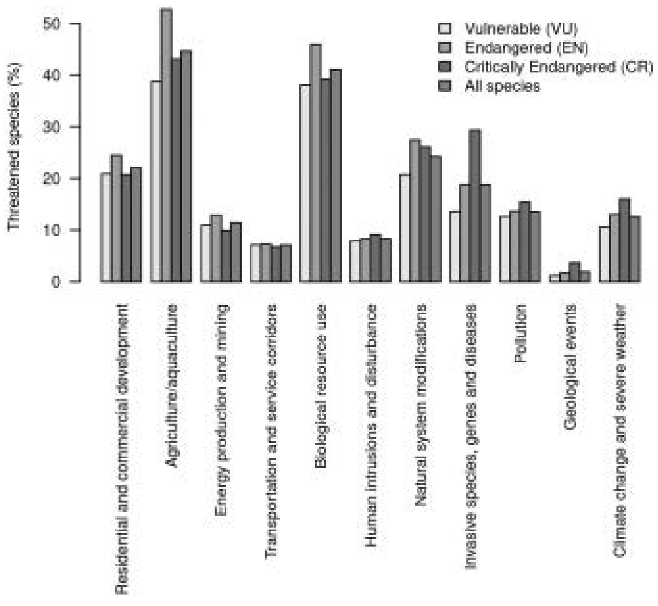

Figure 4. Example of a bar plot summarizing the threats to biodiversity for different Red List categories (vulnerable [VU], endangered [EN], critically endangered [CR], and all categories). According to this plot, the main threats to biodiversity include agriculture/aquaculture and biological resource use (e.g., overfishing and overhunting). Threats such as invasive species, genes and diseases, climate change, and severe weather or pollution are more frequent as the threat category increases (i.e., CR vs. VU and EN).

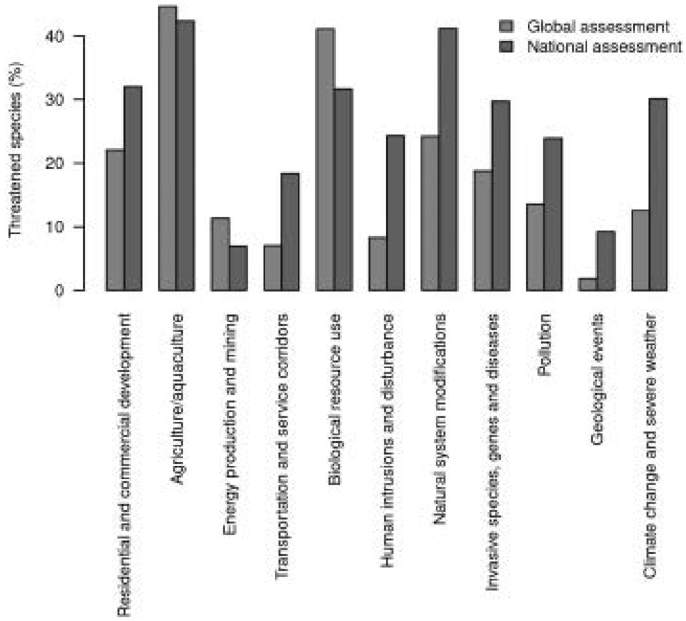

Figure 5. Example of a bar plot comparing major biodiversity threats at the global (blue) and national (red) scales. Percentages are based on all species. For the case study, the results indicate that some threats are more frequent in Spain than worldwide, such as residential and commercial development, transportation and service corridors, human intrusion and disturbance, natural system modifications (e.g., construction of reservoirs), invasive and other problematic species, genes and diseases, pollution, and climate change. Note, the sum of the percentages of threatened species across threats both globally and nationally exceeds 100% because the same species can be affected by several threats simultaneously.

3. Where should conservation actions at the national level be directed?
4. Finally, what is the pattern obtained after summing the percentages of threatened species in the columns for all three categories combined at the global and national levels? What are the implications of the results in terms of biodiversity conservation?

In the first phase, these questions should be addressed individually by students. At the end of the activity, an open discussion is conducted in the classroom to allow students to compare their findings and interpretations of the results. Students discuss the differences in the observed patterns of threats to biodiversity in different geographical regions and infer the underlying processes or mechanisms that might trigger species extinctions in different study regions.

Further options for analysis and discussion might include comparison of threats to biodiversity between plants and animals and/or by habitat types (forests, savannas, scrublands, grasslands, wetlands, etc.).

○ Assessment of the Activity

To analyze the performance of the activity at generating learning outcomes, third-year university biology students conducted the activity as part of a conservation biology course, and they were requested to complete an anonymous survey after finishing the course. In total, 56 students from the 2019/2020 academic course at Rey Juan Carlos University, Spain, were asked to evaluate the acquisition of different key competencies and basic skills as learning outcomes, including awareness of environmental issues, expertise in biological diagnosis, information management, and use of the internet as an information source. Thirty-six respondents completed the survey, and they represented 64% of the cohort. The responses provided by the students were highly variable, but the average scores in all cases ranged between eight and nine, and awareness of environmental issues and using the internet as an information source were the key competencies that received the best ratings from students (Figure 6).

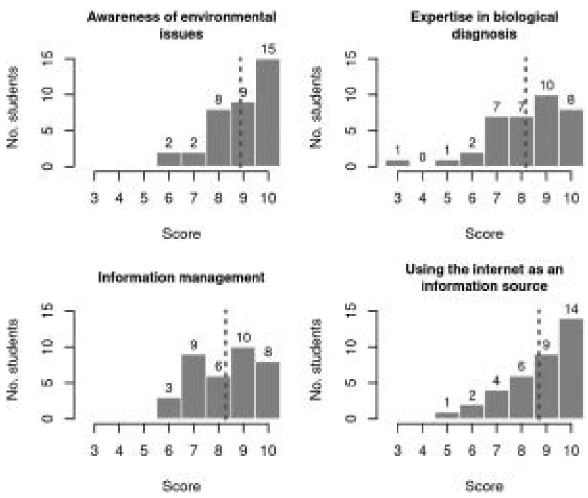

Figure 6. Responses of students to a survey conducted for assessing learning outcomes. The students were asked to score (from 1 to 10) the acquisition of key competencies and basic skills, including awareness of environmental issues and expertise in biological diagnosis, information management, and use of the internet as an information source. Out of 56 students, 36 responded to the survey (64% of the cohort). Dashed lines represent average values.

○ Conclusions

This computer-based activity aims to engage students in exploring the main threats to biodiversity at global and regional scales by using the IUCN Red List. The activity also helps to increase concerns about declines in biodiversity, and thus it is suitable not only for university-level students in courses related to conservation biology but also for senior high school biology students. Conducting the activity can contribute to the development of several key competencies and basic skills, including expertise in biological diagnosis, information management, and using the internet as an information source. These competencies are evaluated during the implementation phase of the activity and in the discussion session where the students compare their results and conclusions.

Supplemental Material

Appendices 1–4 are available with the online version of this article.

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References

Ceballos, G., García, A. & Ehrlich, P.R. (2010). The sixth extinction crisis: loss of animal populations and species. *Journal of Cosmology*, *8*, 1821–31.

Chamberlain, S., Barve, V., Mcglinn, D., Oldoni, D., Desmet, P., Geffert, L. & Ram, K. (2021). *rgbif: interface to the global biodiversity information facility API*. R package version 3.5.2. https://cran.r-project.org/package=rgbif.

Chamberlain, S., Szoecs, E., Foster, Z., Arendsee, Z., Boettiger, C., et al. (2020). *Taxize: taxonomic information from around the web*. R package version 0.9.98. https://github.com/ropensci/taxize.

Ehrlich, P.R. & Ehrlich, A.H. (1981). *Extinction: The Causes and Consequences of the Disappearance of Species*. Random House.

Froese, R. & Pauly, D. (Eds.). (2020, December). *FishBase*. https://www.fishbase.org.

Grassle, J.F. (2000). The ocean biogeographic information system (OBIS): an on-line, worldwide atlas for accessing, modeling and mapping marine biological data in a multidimensional context. *Oceanography*, *13*(3), 5–9.

Guiry, M.D. & Guiry, G.M. (2021). *AlgaeBase*. National University of Ireland, Galway. https://www.algaebase.org.

Hughes, J.B., Daily, G.C. & Ehrlich, P.R. (1997). Population diversity: its extent and extinction. *Science*, *278*, 689–92.

IUCN Standards and Petitions Committee. (2019). *Guidelines for using the IUCN Red List categories and criteria*. Version 14. http://www.iucnredlist.org/documents/RedListGuidelines.pdf.\

Mace, G.M., Collar, N.J., Gaston, K.J., Hilton-Taylor, C., Akcakaya, H.R, et al. (2008). Quantification of extinction risk: IUCN's system for classifying threatened species. *Conservation Biology*, *22*, 1424–42.

Parr, C.S., Wilson, N., Leary, P., Schulz, K.S., Lans, K., et al. (2014). The Encyclopedia of Life v2: providing global access to knowledge about life on Earth. *Biodiversity Data Journal*, *2*, e1079.

Purvis, A., Gittleman, J.L., Cowlishaw, G. & Mace, G.M. (2000). Predicting extinction risk in declining species. *Proceedings of the Royal Society of London B*, *267*, 1947–52.

Raup, D.M. (1994). The role of extinction in evolution. *Proceedings of the National Academy of Science*, *91*, 6758–63.

Sullivan, B., Wood, C., Iliff, M.J., Bonney, R.E., Fink, D. & Kelling, S. (2009). eBird: a citizen-based bird observation network in the biological sciences. *Biological Conservation*, 142, 2282–92.

Vitousek, P.M., Mooney, H.A., Lubchenco, J. & Melillo, J.M. (1997). Human domination of Earth's ecosystems. *Science*, *277*, 494–99.

Yesson, C., Brewer, P.W., Sutton, T., Caithness, N., Pahwa, J.S., et al. (2007). How global is the Global Biodiversity Information Facility? *PLoS ONE*, *2*(11): e1124.

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INQUIRY & INVESTIGATION

Cannus stannous: Understanding Chance & Necessity in Natural Selection

NABT BioClub RECOMMENDATION

DOUGLAS ALLCHIN

Abstract

This classroom activity highlights how evolution by natural selection is nonteleological*—that is, not guided by need, by organismal intent, by inherent progress, by an external ideal, or by any observable purposive agent. Rather, it is driven by chance opportunity, environmental context, and historical happenstance. Students simulate the evolution of a population of tin cans, based on temperature retention/loss in either arctic or hot desert habitats. Chance and necessity interact in separate lab groups (as isolated populations), based on similar starting organisms. The process demonstrates not only selection but also how even organisms in similar environments may not evolve with identical traits, depending on available mutations. It shows that even when selection occurs, it may not do so consistently or uniformly with each generation. It shows both divergence based on different contexts of selection and variability based on the vagaries of history.*

Key Words: *natural selection; evolution; teleology; chance; simulation*

○ Orientation

Cannus stannous. Surely you recognize the scientific name of an organism commonly found in recycling bins? The *tin can*. Here, I describe a classroom activity that highlights how evolution by natural selection is *nonteleological*—that is, not guided by need, by organismal intent, by inherent progress, by an external ideal, nor by any observable purposive agent. Rather, it is driven by chance opportunity, environmental context, and historical happenstance. Students simulate the evolution of a population of tin cans, based on temperature retention/loss in either arctic or hot desert habitats. Chance and necessity interact in separate lab groups (as isolated populations), based on similar starting organisms, but leading to divergent outcomes. Personal engagement helps render these nonintuitive concepts concrete. It's a fun "wet lab"—literally, with lots of water!

While students will see the expected adaptation from selection, they will also witness the various effects of chance.

Educators have long been concerned about how to teach evolution and natural selection effectively. While this lab activity illustrates the standard concepts—adaptation, mutation, variation, inheritance, selection, reproductive fitness, and divergence—the main focus is not the mechanism of change but rather the ***nature*** of the evolutionary process. Most students initially regard natural processes, including evolution, as purposive (e.g., Allchin, 2021; Kelemen, 2004, 2012; Varella, 2018; Werth & Allchin, 2020). Accordingly, polls consistently find that even among Americans that view humans as evolved, roughly two-thirds also view the process as guided or involving an intentional agent (Pew Research Center, 2019; Swift, 2017). In this regard, they are not that different from those who reject evolution outright as incompatible with a religious view of providential agency (e.g., Ashley, 2016; Moore et al., 2002). Not surprisingly perhaps, teleological views are frequently cited as an obstacle in students understanding evolution (e.g., Bishop & Anderson, 1990; Stover & Mabry, 2007; Gregory, 2009; Mead & Scott, 2010a; González Galli & Meinardi, 2011; Gelman & Rhodes, 2012; Barnes, et al., 2017; Gresch, 2020). Addressing teleological perspectives thus seems essential, even foremost, in teaching about evolution (e.g., Bardapurkar, 2008; Greene, 1990). The lab activity here thus focuses chiefly on the role of chance (elaborated ahead) and its interplay with necessity in natural selection and evolution.

One effective strategy for addressing teleological views is through historical cases (Jensen & Finley, 1995). Many textbooks discuss Darwin's voyage on the *Beagle*, and some detail the development of his ideas. Using the parallel case of Alfred Russel Wallace, Friedman (2010) further integrates history with student inquiry, thereby incorporating another pedagogical ideal: active, problem-based learning. The strategy here, however, is to help students experience first hand, through a simulation of evolution, how chance factors into natural selection. It yields observations that challenge the intuitive views that adaptation naturally tends toward imagined

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or desired ideals. It thereby opens the way for conceptual change through subsequent moderated discussion.

Many (many!) activities for simulating natural selection are already available (e.g., in this journal: Baumgartner & Duncan, 2009; DeSantis, 2009; Hongsermeier et al., 2017; also Geraedts & Boersma, 2006; Janulaw & Scotchmoor, 2011; plus many readily available virtual computer models). However, most focus just on the standard mechanistic concepts listed above, not teleology. They typically use predation of colored prey (LEGO blocks, beads, jelly beans) against colored backgrounds—simple examples that students readily appreciate. Almost all activities seek primarily to "rationalize" adaptive design as arising from thoroughly naturalistic processes, using the student as an active selecting agent, ironically affirming teleological views (Table 1).

Few explore the role of other evolutionary outcomes, such as divergence, convergence, biogeographical patterns, founder effects, exaptation, or vestigial structures. Some activities do try explicitly to address "Lamarckian" concepts (whether characterized as individual-level adaptation, use and disuse, inheritance of acquired traits, or "need"/*besoin*; Bishop & Anderson, 1990, p. 422). Yet a common refrain from research is that they generally fail to do so. For example, as reported recently in this journal, Bauer (2017) achieved significant pre-post gains with a simulation involving imaginary organisms. However, the activity was *not* effective on two key elements surrounding teleology: whether adaptations arise out of need and whether individuals themselves mediate the adaptive process (pp. 123, 125). Likewise, Geraedts and Boersma (2006) found it difficult to dislodge Lamarckian preconceptions while trying to demonstrate the creative role of chance variation. By comparison, the *Cannus stannous* simulation aims foremost to highlight the role of arbitrary factors (or chance), even when organisms may also ultimately exhibit apparent "design." Teachers who already use other simulations may find features here that help them revise or extend their own activities to address teleological preconceptions more effectively.

Jacques Monod famously characterized evolution as an interplay of "chance and necessity." However, the ambiguous term *chance* may well invite some caution (Mead & Scott, 2010b). In the activity here, *chance* signifies inherent uncertainty, or happenstance—that is, without an explicit or intentional trajectory—the very opposite of necessity. When biologists refer to chance variation, for example, they mean that mutations are "blind": not biased by the status of the organism or its environment, or toward improved functionality. One may contrast this with other familiar (but inappropriate) meanings of *chance* that allude to mathematical probabilities, such as random, stochastic, rare, or infrequent. Hence, when one rolls a die in the exercise here, it is not to assign a numeric frequency to the various alternative events but rather to represent their inherent unpredictability. One may thus associate chance with historical *contingency*: coincidence, or the unforeseeable intersection of historical events, or the fortuitous combination of contexts that cannot be anticipated, or, more simply, *happenstance* (on contingency, see Jacob, 1977; Gould, 1989; Andrews & Burke, 2007; Blount et al., 2018). Chance yields opportunity, not determinism. It opens potentialities rather than unfolding preordained plans. Accordingly, one might equally call evolution an interplay of contingency and necessity.

○ Overview

The objective of the *Cannus stannous* simulation is to underscore the interaction of unpredictable opportunity and necessity in evolution and to show that the process of natural selection is indirect (two-stage), *not* teleological and *not* observably governed by intentional agency.

This is a summary only. For a complete description, see the Supplemental Material available with the online version of this article. This includes a student handout (S1) and teaching notes (S2, especially helpful where instructors rely on teaching assistants).

The strategy is to use a hands-on simulation, where rolls of the die are recognizably uncontrolled, indeterminate events in generating new variants (mutations). Students manage the differential survival of a model organism (the tin can) based on how well they retain (or lose) heat. The class is split into two environments (arctic and desert) to show how selection will foster divergence in different habitats, even when everyone starts with identical populations. Chance mutations are introduced every generation. Similarly, each

Table 1. Student misconceptions based on various teleological views (interpretations of "purpose") in typical simulation activities.

Preconception	Apparently Confirming Observation	Resonance with Target Concepts
inherent progress / "force" of improvement	• All populations exhibit adaptive trends.	natural selection (but note role of *unpredictable* origin of variants!—underscores role of contingency in selection, not direct transformation)
design, adaptive "purpose"	• Different populations' traits change appropriately to their respective environment.	natural selection (but note role of *blind* variation!—underscores role of "chance" in selection, not direct transformation) divergence (but note role of *isolated* populations)
"survival of the fittest" (competition rewards winners only)	• Organisms with higher fitness values tend to survive and reproduce.	natural selection (but note creative role depends on opportunity of new variants and "chance" vagaries of individual life)

lab table is an "island" (sharing an environment with others), as a way to underscore how unpredictable sources of variation in geographically isolated locations typically yield different histories and different outcomes. Students eventually compare results and reason about their similarities and differences.

While this simulation, like many other simulations, illustrates several basics of natural selection (variation, differential survival/reproduction, inheritance, mutation, adaptation, divergence), the primary aim is to underscore a pair of central concepts about the nature of the evolutionary process:

- the role of *unintended, nondirectional variation* in natural selection, still leading to adaptation or what we interpret as "good design"—using die rolls
- the role of *divergence* in *geographically isolated* populations, where unpredictable local events (again, die rolls) introduce different variants and histories.

That is, while students will see the expected adaptation from selection, they will also witness the various effects of chance, not in accord with widespread intuitions about intentional agency and purposive action. Chance also yields arbitrary divergence, not merely adaptive selection.

First, designate one half of the classroom as arctic, the other half as hot desert—which simply determines where selection will be based on temperature retention (arctic) or temperature loss (desert). Every lab group/table is provided with an identical initial population: four "wild-type" tin cans, which are 12-ounce, bare metal skin, and half full (see Figure 1).

They add hot water to the cans (here, to start, half full) and measure the initial temperatures. After 10 minutes, they measure temperature again to determine the heat loss in each can. Two of the four individuals are then selected, based on the designated habitat. In the arctic habitat, one selects for heat retention (least temperature decrease). In the desert habitat, one selects for heat loss (the two cans with the greatest temperature drop). Each surviving can "reproduces," yielding a duplicate. Mutations are then introduced with the roll of a die, independently for each of the three traits for each of the four cans (see the chart in the student handout, Supplemental Material S1, for details on how each number codes for a different change in trait). Some cans will become larger, some smaller. Some will have more water (three-quarters full), some less (one-quarter full). Some will acquire insulation (students need to add an insulating layer), others thermal venting (they add a wet covering). All unpredictable. Roll the dice for the mutations for all four cans separately: lots of opportunities for chance variation! Add up the new fitness value for each can (see chart in student handout, Supplemental Material S1). Begin a graph of the population's average fitness value vs. time (generation number). The newly mutated surviving cans are refilled with fresh hot water (to their new levels), and the process repeats (Figure 1). Students follow their population for several generations (ideally six), recording phenotypes and fitness values, graphing them as they go. As students wait for their generations to mature, the instructor circulates, helping to reinforce understanding of the analogies of the model (Table 2).

The repeated roll of the die may seem redundant, time consuming, or boring. Roll. Roll again. Roll again. Twelve times each generation. But addressing this element of contingency over and over functions experientially to underscore its pervasive role, central to the activity's main lesson.

For a detailed summary of materials and setup, see the teaching notes (Supplemental Material S2).

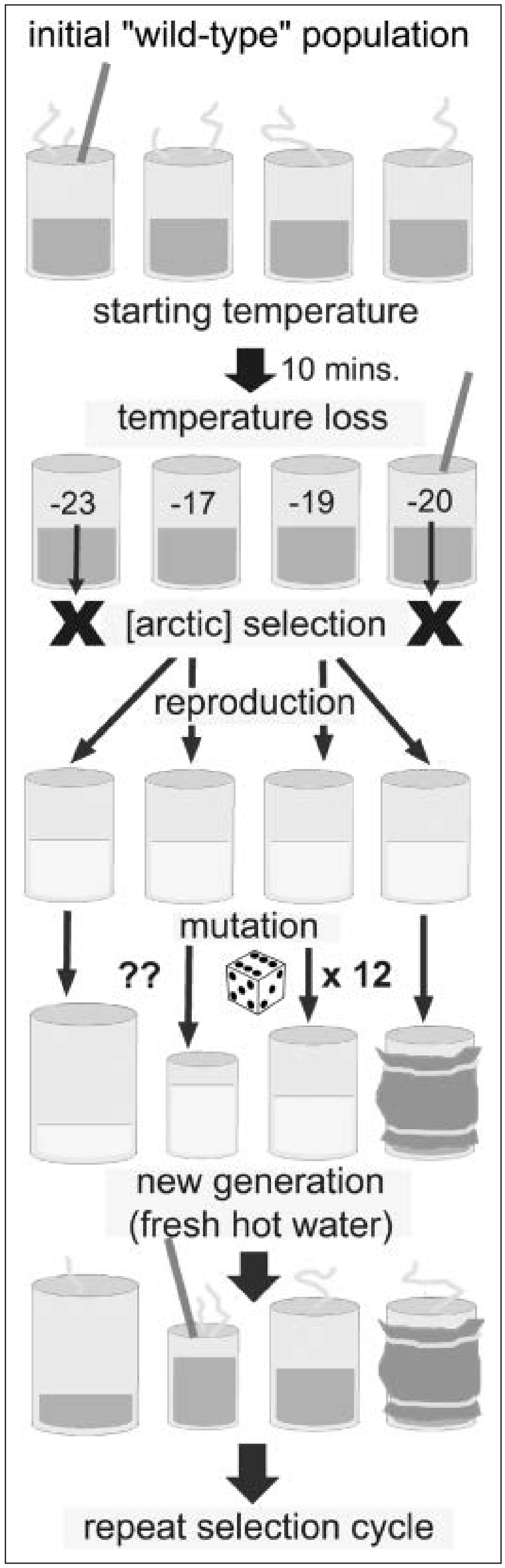

Figure 1. Visual guide to the basic procedures. Diagram does not show calculation of fitness values; graphing results for each generation; coding for how to translate dice rolls into physical mutations regarding can size, water level, or skin type (see chart in student handout, Supplemental Material S1); or questions from the instructor to prompt inquiry reflection (see teaching notes, Supplemental Material S2, and Tables 1–3).

Table 2. Analogies of the model.

Natural World	*Cannus stannous* model
blind variation	roll of die
selection	limited survival—only 2 of 4 reproduce
environment	arctic (heat retention) vs. desert (heat loss)
geographical isolation	separate lab tables

Note that this lab is more than a cookbook demonstration of (highly predictable) directional selection (see Table 1). It is not easily completed on one's own. Inquiry is involved, and instructor questioning is integral to the learning activity (see Table 3).

As the activity proceeds, students are prompted to notice and consider how to explain certain puzzling results (see student write-up as described in the student handout, Supplemental Material S1). For example, do all the mutations match or respond to the organisms' "needs"? If not, how can the population change adaptively? (Here is the core lesson about the alternating effects of chance and necessity.) Does the tin can's behavior influence the subsequent mutations? (No, it's inert! Adaptations arise by chance mutation—the roll of the die, unrelated to the can or the environment.) Usually, there is at least one case per class where average fitness *decreases* in a given generation: how does one explain *that*?! (Again, it's chance: the unpredictable roll of the die.) Later, as the varying results from different lab groups becomes clear, how does one explain how groups following the very same procedure in the same environment could lead to different results? Namely, why are all the adaptations not exactly the same? (Yet again, the role of unpredictable, or chance, variation.) If we started again, would you expect the same outcome? (No, not exactly! General trends, probably yes.) How would each new mutation affect temperature loss and survival in the other environment? Is any particular mutation inherently beneficial or detrimental? (No, survival value depends on context, not on the mutation itself.) Every population started with the same traits and experienced the same "rules" in introducing variants, yet traits in the desert and arctic habitats eventually diverged: Why? (Chance yet again!) Do the cans

Table 3. Various teleological views (interpretations of "purpose") and how they are addressed in this activity. (Citations indicate documentation of preconceptions.)

Preconception (Teleological Misconception)	Anomalous Observation, or Discrepant Event	Target New Concept
Source of Variation		
Inherent progressive force.[4,6]	• In some cases, overall fitness decreased in a given generation. • Fitness value did not exhibit uniform gain for every trait in every generation. • All populations received the same set of mutations, but each was beneficial in one environment, detrimental in the other.	The origin of variation is unpredictable – and its adaptive meaning depends on context. Role of "chance," or contingency. Still, when such variation is coupled with selection, adaptation is possible.
"Need" / Lamarckian *besoin*.[1,2,3,4,5,6]	• New variants did not always enhance survival value. • Mutations depended solely on the roll of the die, not the status of the organism.	The origin of variation is blind to need. Role of chance, lack of a targeted goal. Still, when blind variation is coupled with selection, adaptation is possible.
Mediated by organismal intent or agency (perhaps by behavior, use, will, want, or desire).[1,2,3,4,6]	• The tin cans were "passive" and did not exhibit any behavior relevant to their survival or inheritance. Mutations depended solely on the roll of the die; selection on temperature loss.	Variation arises unpredictably, contingently. Selection depends on the environment.
Mediated by external or environmental intent or "purpose."[2,4,6]	• Adaptation was achieved without applying any intention on our part. Reproduction for each successive generation was shaped solely by differential survival (temperature loss). • Mutations depended solely on the roll of the die, not the status of the environment.	Natural selection integrates both blind variation and differential survival.

Inheritance		
Inheritance of acquired traits (including use/disuse), or organisms choose which traits to pass on.[1,2,3,4,6]	• The tin cans did not change themselves in any way. Inheritance was based solely on survival, relative to temperature loss.	Natural selection is based on differential survival, leading to reproduction and inheritance.
Nature of Transformation		
Organisms transform themselves, based on individual determination or agency (selection not needed, or is redundant).[1,2,3,4,6]	• No change occurred without either differential survival or an unpredictable new variant.	Natural selection is not direct transformation, but an indirect creative process combining both blind variation and differential reproduction.
Environmental determinism ("strong design").[1,3,4]	• Different populations within the same environment did not exhibit exactly the same adapations.	Unpredictable mutations in isolated lineages yield different variants and separate histories. Role of chance.
Survival of the fittest (competition rewards winners only).[1,4]	• Can with the highest fitness value did not always retain (or lose) more heat (and hence, survive).	Natural selection is opportunistic and contingent, not strictly deterministic. Role of chance.

(1) Bishop & Anderson (1990); (2) Stover & Mabry (2007); (3) Bardapurkar (2008); (4) Gregory (2009); (5) Brumby (1984); (6) Greene (1990)

"know" how to adapt? (Not possible! Again, the cans are inert, passive, and hardly conscious.) The instructor checks around the classroom, inviting students to compare events with their expectations (documented earlier), thereby engaging students with their preconceptions.

All these questions help prime reflections for the critical discussion afterward. When the results are all collected, the instructor helps the different groups compare them. Where are there similarities, where are there differences? How do we explain them? In other words, the instructor should guide awareness of all the key comparisons and ensure effective reasoning about the interaction of chance and selection (Table 3). Each student writes up their conclusions independently, allowing individual assessment.

○ Supplemental Material

Available with the online version of this article:

- *S1.* Student handout
- *S2.* Teaching notes

○ Acknowledgments

This activity is adapted from a version used by Mark Schlessman at Vassar College in the 1980s, from an even earlier (unpublished) original. I received it from Bill George at Georgetown Day High School in Washington, DC, and recrafted it to emphasize teleology. I share it here, fully expecting *Cannus stannous* to mutate further in future classroom generations, perhaps hybridize, and ultimately adapt to local teaching environments. My humble appreciation to Glenn Branch, Robert Cooper, Robert Dennison, Leonardo Gonzalez-Galli, Gaston Perez, Alex Werth, and anonymous *ABT* reviewers for helpful comments on the text.

References

Allchin, D. (2021). Why do platypuses fluoresce? Or why Darwin did not believe in "evolution." *American Biology Teacher*, 83, 555–559.

Andrews, T. & Burke, F. (2007). What does it mean to think historically? *Perspectives on History*, *45*(1). https://www.historians.org/publications-and-directories/perspectives-on-history/january-2007/what-does-it-mean-to-think-historically.

Ashley, J.M. (2016). Is it providential, by chance? Christian objections to the role of chance in Darwinian evolution. In Ramsey, G. & Pence, C.H. (Eds.), *Chance in Evolution* (pp. 103–21). University of Chicago Press.

Bardapurkar, A. (2008). Do students see the "selection" in organic evolution? A critical review of the causal structure of student explanations. *Evolution: Education and Outreach*, *1*, 299–305.

Barnes, M.E., Evans, E.M., Hazel, A., Brownell, S.E. & Nesse, R.M. (2017). Teleological reasoning, not acceptance of evolution, impacts students' ability to learn natural selection. *Evolution: Education and Outreach*, *10*(7).

Bauer, S. (2017). The impact of the chukwin mini-unit on students' understanding of natural selection. *American Biology Teacher*, *79*(2), 120–27.

Baumgartner, E. & Duncan, K., (2009). Evolution of students' ideas about natural selection through a constructivist framework. *American Biology Teacher*, *71*(4), 218–27.

Bishop, B.A. & Anderson, C.W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching*, *27*(5), 415–27.

Blount, Z.D., Lenski, R.E. & Losos, J.B. (2018). Contingency and determinism in evolution: replaying life's tape. *Science, 362*(6415), eaam5979.

DeSantis, L. R. (2009). Teaching evolution through inquiry-based lessons of uncontroversial science. *American Biology Teacher*, *71*(2), 106–11.

Friedman, A. (2010). *Alfred Russel Wallace & the Origin of New Species*. SHiPS Resource Center. http://shipseducation.net/modules/biol/wallace.htm.

Gelman, A.S. & Rhodes, M. (2012). "Two-thousand years of stasis": How psychological essentialism impedes evolutionary understanding. In Rosengren, K.S., Brem, S.K., Evans, E.M., & Sinatra, G.M. (Eds.), *Evolution Challenges: Integrating Research and Practice in Teaching and Learning about Evolution* (pp. 3–21). Oxford University Press.

Geraedts, C.L. & Boersma, K.T. (2006). Reinventing natural selection. *International Journal of Science Education*, *28*(8), 843–70.

González Galli, L. & Meinardi, E.N. (2011). The role of teleological thinking in learning the Darwinian model of evolution. *Evolution Education and Outreach*, 4, 145–52.

Gould, S.J. (1989). *Wonderful Life*. W.W. Norton.

Greene, E.D. (1990). The logic of university students' misunderstanding of natural selection. *Journal of Research in Science Teaching*, *27*, 875–85.

Gregory, R.T. (2009). Understanding natural selection: essential concepts and common misconceptions. *Evolution: Education and Outreach*, *2*, 156–75.

Gresch, H. (2020). Teleological explanations in evolution classes: video-based analyses of teaching and learning processes across a seventh-grade teaching unit. *Evolution: Education and Outreach, 13*, 10.

Hongsermeier, A., Grandgenett, N.F. & Simon, D.M. (2017). Modeling evolution in the classroom: an interactive LEGO simulation. *American Biology Teacher, 79*(2), 128–34.

Jacob, F. (1977). Evolution and tinkering. *Science*, 196, 1161–1166.

Janulaw, A. & Scotchmoor, J. (2011). Clipbirds. University of California, Berkeley's Lawrence Hall of Science. https://www.howtosmile.org/resource/smile-000-000-003-159.

Jensen, M.S. & Finley, F. (1995). Teaching evolution using historical arguments in a conceptual change strategy. *Science Education, 79*, 147–66.

Kelemen D. (2004). Are children "intuitive theists"? Reasoning about purpose and design in nature. *Psychological Science*, *15,* 295–301.

Kelemen, D. (2012). Teleological minds: how natural intuitions about agency and purpose influence learning about evolution. In Rosengren, K. & Evans, E.M. (Eds.). *Evolution Challenges: Integrating Research and Practice in Teaching and Learning about Evolution*. Oxford University Press.

Mead. L.S. & Scott, E.C. (2010a). Problem concepts in evolution part I: purpose and design. *Evolution: Education and Outreach*, *3*, 78–81.

Mead. L.S. & Scott, E.C. (2010b). Problem concepts in evolution part II: cause and chance. *Evolution: Education and Outreach*, *3*, 261–64.

Moore, R., Mitchell, G., Bally, R., Inglis, M., Day, J. & Jacobs, D. (2002). Undergraduates' understanding of evolution: ascriptions of agency as a problem for student learning. *Journal of Biological Education, 36*, 65–71.

Pew Research Center. (2019). *Evolution, Creationism, Intelligent Design*. https://news.gallup.com/poll/21814/evolution-creationism-intelligent-design.aspx.

Stover, S.K. & Mabry, M.L. (2007). Influences of teleological and Lamarckian thinking on student understanding of natural selection. *BioScene*, *33*(1), 11–18.

Swift, A. (2017). In U.S., belief in creationist view of humans at new low. Gallup. https://news.gallup.com/poll/210956/belief-creationist-view-humans-new-low.aspx.

Varella, M.A.C. (2018). The biology and evolution of three psychological tendencies to anthropomorphize biology and evolution. *Frontiers in Psychology*, *9*, 1–21.

Werth, A. & Allchin, D. (2020). Teleology's long shadow. *Evolution: Education and Outreach, 13*(4).

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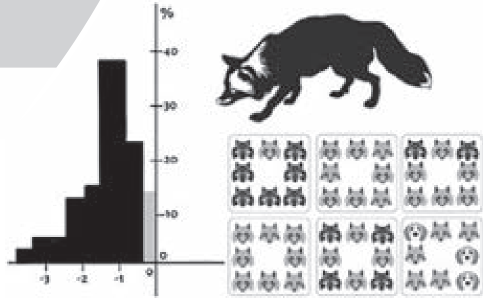
INQUIRY & INVESTIGATION

Inquiry-Based Activities for Teaching about Natural Selection: Dog Evolution & the Secret Ingredient of an Amazing Experiment

RECOMMENDED FOR *AP Biology*

PAOLA NÚÑEZ, PABLO CASTILLO, CLAUDIA HINOJOSA, CAROLINA PARRAGUEZ, HERNÁN COFRÉ



Abstract

Teaching evolution is one of the most difficult tasks in biology education since there are a great variety of obstacles to its understanding. The inclusion of the nature of science and scientific inquiry, the connection with aspects of daily life, work based on scientific argumentation, and the use of empirical studies from current research have been identified as important aspects to include in teaching evolution. In this work, we present a series of three activities, which were developed after considering all the recommendations of the literature described above. The sequence begins with the example of the evolution of one of the species most loved by students: dogs. Through argumentation, students make their preconceptions explicit. After this, a long-term experiment about artificial selection in the silver fox (Vulpes vulpes) *is presented (see Glaze, 2018) as part of the reflection on the experimental evidence that supports evolution. Finally, students are asked to generate a hypothesis about how they think the domestication process of wolves occurred, eventually resulting in dogs. The outcomes of implementation in high school classrooms and biology teacher education are discussed.*

Key Words: *natural selection; nature of science; evolution of dogs; silver fox experiment.*

○ Introduction

In 1973, in this journal, Theodosius Dobzhansky developed an argument in favor of the validity of the theory of evolution as an explanation of the diversity and unity of life. Almost 50 years later, research in evolution education has shown that teaching effectively for this content is still a great challenge for several reasons. However, there are some strategies that can help biology teachers eventually overcome the intuitive explanations that students have about evolution (Harms & Reiss, 2019). A first approach seems to be including the nature of science (NOS), either before the teaching of evolution or integrated with it (Cofré et al., 2018; Scharmann, 2018). The inclusion of NOS, or the understanding of how scientists work and how scientific knowledge is created, validated, and influenced (McComas, 2018), should serve mainly to show students that evolution is both a fact and a good scientific theory with solid empirical evidence and great explanatory power (McComas, 2018). This implies, then, that it might be useful to have students work with actual data and real examples of evolution (Lucci & Cooper 2019) to reflect on the theory of evolution and to fulfill the element of NOS, whereby science requires empirical evidence (McComas, 2018). Students must also understand that the evidence does not always come from experimental results (although there is such evidence) but also from geographic, taxonomic, and molecular comparisons; that is, science uses multiple methods (McComas, 2018). In addition, Glaze and Goldston (2015) established that student-centered teaching, which includes active learning, is an effective approach. For example, teaching using computational simulations, in which students can manipulate population variables of real species (e.g., snails, birds, lizards or fish), to investigate and not just to play, has been proposed as an effective strategy to achieve understanding of the process of natural selection (e.g., Hodgson 2019; Malone, et al., 2019). On the other hand, when evolution is related to aspects of students' daily lives, they are more likely to understand its relevance and are more motivated to work on developing an understanding of related content (Sinatra et al., 2008). This can be attained with laboratories where students must answer questions about how a population of bacteria can develop resistance to antibiotics (Williams, et al., 2018), or with the analysis of data on how humans have developed different adaptations (e.g., the evolution of skin color or the relationship between malaria and sickle-cell anemia) (Pobiner et al., 2018). Finally, argumentation, as a skill inherent to scientific activity, has been proposed as a propitious strategy to challenge the naive ways of thinking that students have about evolution (Osborne et al., 2017).

> *[We] present three examples of activities with different dynamics, where argumentation, the use of models, and the incorporation of the NOS are used in an inquiry-based strategy.*

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In this paper, we present a sequence of three activities for the teaching of natural selection within a context that motivates students due to familiarity: the evolutionary origin of dogs from an ancestral wolf population. Dogs are a phenotypically diverse group that consists of at least 400 genetically distinct breeds. Dogs (*Canis familiaris*) and Eurasian wolves (*Canis lupus*), as indicated by their species names, belong to the same genus. However, only dogs have been domesticated by humans. In the first activity, students are asked to argue about which of the three proposed hypotheses is the most correct; then, the hypothesis is contrasted with the empirical data of a study on the domestication of the silver fox (*Vulpes vulpes*), carried out by the Russian geneticist Dmitry K. Belyaev in 1959 (Trut & Dugartkin, 2017); the concluding activity is the development of a model of the evolution of dogs from wolves.

○ Overview of Activities

The three activities are considered to form a learning cycle like that proposed by Karplus (1977), with three phases: (1) exploration, (2) introduction, and (3) concept application. The first two activities are expected to bring students into a conceptual conflict situation, which can promote conceptual change (Nehm & Kampourakis, 2016). In Activity 1, planned for a 90-minute lesson, students are expected to reflect on their own knowledge regarding the familiar phenomenon of the presence of dogs in human life. Based on this familiar experience, students are encouraged to face the new experience of trying to explain how this species could have evolved from an ancestral species, such as wolves living today. To guide this discussion, groups are formed, and three possible explanations are presented to promote dialogic argumentation (Osborne et al., 2017). Figure 1 shows the worksheet that can be used with students. It is expected that this activity will make misconceptions about need or use and disuse emerge, which, in the first instance, should be challenged by the explanation of natural selection that some students can adopt. The misconception that "evolution is not something we see in our daily lives" is also addressed. At the end of the activity, teachers can include more information about the scientific evidence that supports the evolution of dogs as the first species domesticated by humans, either through news (e.g., Funk, 2020; Pavlidis & Somel 2020) or by reading excerpts from scientific articles about dog evolution (e.g., Kaminski et al., 2019; Bergström, et al. 2020). For a summary of scientific information about dog evolution, see Appendix S1 (in the Supplemental Material available with the online version of this article). It is important to make students realize that scientists annually publish new evidence of dogs' evolution, and that sometimes there are controversies among them, but there is no controversy about whether the origin of dogs is by evolution, or if the process that explains it is natural and artificial selection.

If there are still doubts about the validity of the other possible explanations (the inheritance of acquired characteristics or intentionality), the teacher can propose that each group generate a prediction associated with the explanation they like the most. This proposal can be accompanied by the following question: How could we experimentally verify that the hypothesis of the evolution of the dog by natural selection is a good scientific explanation?

In Activity 2, the learning objective is to analyze and interpret data to provide evidence that changes in wild populations can be understood by studying examples of artificial selection that are analogous to natural selection. Students are expected to understand core ideas about natural selection after being exposed to experimental evidence of artificial selection, which is an analogy of the former. The preconception that "evolution acts on a single trait (gene) at a time" is addressed, as well as the preconception that "evolution only occurs after millions of years" (see the worksheet in Appendix S2, in the Supplemental Material available with the online version of this article). In this activity, students are confronted with the empirical data obtained through the artificial selection experiment carried out with the silver fox by Dmitry Belyaev and Lyudmila Trut (Belyaev 1979; Dugatkin, & Trut 2017; Trut & Dugatkin, 2017; see also Glaze, 2018). It is suggested that teachers begin by presenting the problem to be investigated to students for them to propose a hypothesis and an experimental design. Then, teachers present the Belyaev experiment, emphasizing elements that make this research an evolutionary experiment (the presence of a control group, experimental treatment, controlled variables, predictions, the results, and conclusions). It is expected that students will be able to build a better

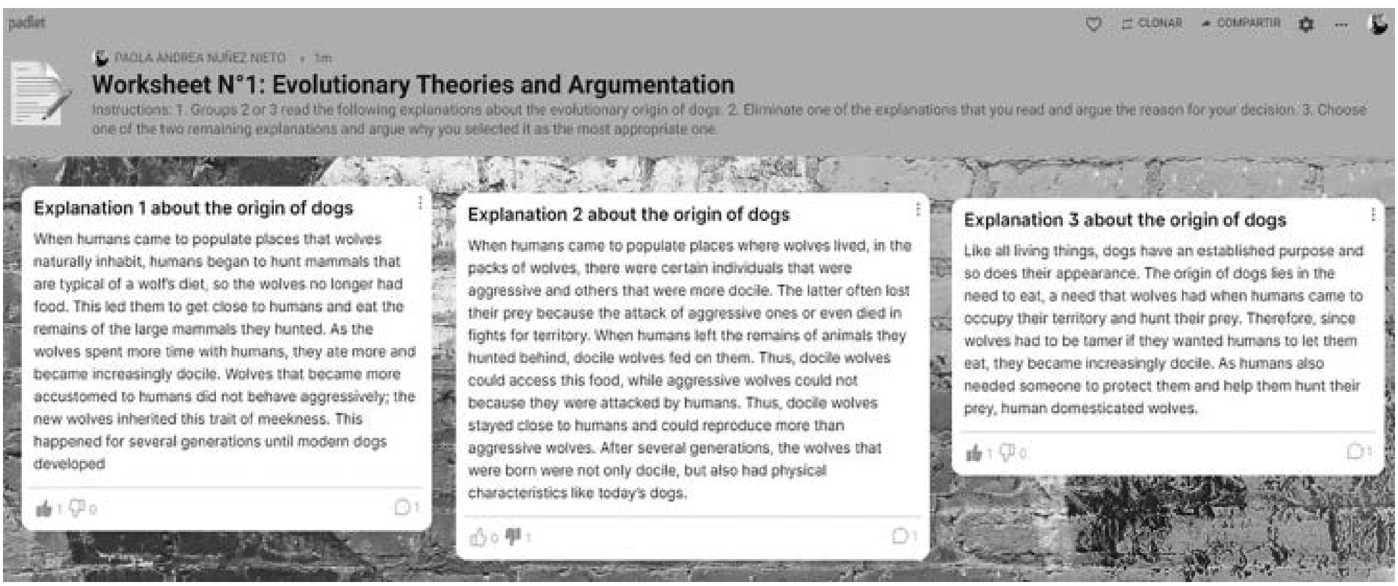

Figure 1. Student worksheet to carry out Activity 1 on explanations of evolutionary change and argumentation. The structure of the guide and its version through the application Padlet for remote work are presented (https://padlet.com).

hypothesis about the origin of dogs, using this study as an example of artificial selection and allowing us to reveal characteristics of the nature of science and its importance to grasp how knowledge is built in science (e.g., the "empirical evidence is required" and "science uses multiple methods" elements of NOS, McComas 2018).

In Activity 3, the learning objective for students is to use the theory of evolution by natural selection and its postulates of variation, differential reproduction, and inheritance with the example of the origin of dogs from an ancestral population of wolves. The strategy of creating explanatory models is used, where it is expected that students can use the different concepts reviewed in the previous activities to generate a plausible scientific hypothesis about the origin of dogs. Because Activity 1 presents natural selection and Activity 2 presents artificial selection, students should wonder whether artificial, natural, or both processes are required. Appendix S3 (in the Supplemental Material available with the online version of this article) shows the activity worksheet. Students are expected to build an explanatory model using the concrete material found on the group worksheet. To represent the evolutionary process, a modified version of the dog evolution model presented in Kampourakis (2014) is used. The parts of the model can be offered to students on a cut-and-paste worksheet (if it is a face-to-face class) or on a digital whiteboard such as Jamboard (if the class is virtual). Figure 2 shows some models created by ninth-grade students. After creating a hypothesis for dog evolution, each group shares it with the class. At this stage, the teacher allows students to reflect on how the changes in their proposals occurred, where the elements of natural and/or artificial selection are found, and to observe that evolutionary changes occur in populations and not in individuals. Caution should be taken that students reflect on the concept of the model and how the proposal is a simplification of the process that occurred (e.g., the process in the model is offered as a linear process, which is not necessarily correct).

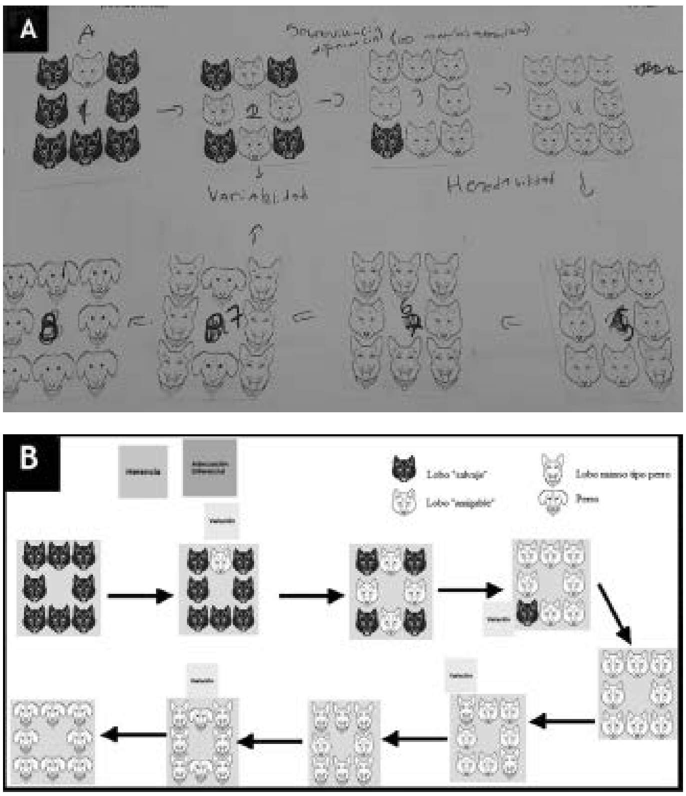

Figure 2. Example of a student worksheet to carry out Activity 3 about explanations of evolutionary change and argumentation in (**A**) face-to-face lessons and (**B**) virtual lessons using Jamboard.

○ Results

Teacher Reflection

The activities presented here were designed to be done in groups where students address previous ideas (see Table 1 for an example), thus creating an opportunity to reconstruct the scientific meaning of the phenomenon under study. For example, in Activity 1 at the beginning of the review of the topic of evolution, many of the students' explanations include need as a force of evolutionary change—or even hybridization—for the generation of a new species (dogs). Table 1 displays an excerpt from a discussion among ninth-grade students (14–15 years old) in which it is evident that some of the participants find it difficult to believe or understand that there is variation in the traits of a population, and rather see evolution as the change of every individual due to need.

When carrying out activities 2 and 3 with students, as pre-service and in-service biology teachers, we realized that it is very motivating to discuss and learn about the evolution and origin of a species as familiar as dogs (Figure 3). Sometimes it is also difficult for participants to identify the selective pressure; that is, what caused tame wolves to be selected during their interactions with humans. In the second activity, it is hard for participants to grasp that the evolution of certain traits can occur (as a change in the gene frequency of a gene in the population) as an epiphenomenon; that is, as a product of selection pressure on another trait (morphology vs. tameness). Finally, in activities 1 and 3, it is also difficult for students to see that a behavioral trait (tameness) can be an adaptation. They are more used to understanding adaptations as morphological traits. For all this, in all

Table 1. Excerpt from a discussion among three ninth-grade students in the context of Activity 1.

S1	The explanation was that they started looking for food. From then, the dogs that we know now were born. Explanation 2 is that there were some cute dogs and others that were angry. The cute ones went with the humans and reproduced.
S2	And the angry ones were left alone.
S1	The angry ones were left alone; they correspond to the current wolves and the other wolves are the dogs we know today. Explanation 3 says that the dogs were domesticated on their own and from then on, the dog developed.
S2	Which do you think is the best?
S3	I like number 2.
S1	I think 3 should be eliminated.
S2	Why do you have to get 3?
S1	No, we must get out explanation number 2.
S2	Delete number 2?
S1	I say that we must eliminate 2, because wolves, like dogs, act in packs, so if some of them go to a place, the whole pack will surely follow them. Therefore, I do not think there is a group of angry [wolves] and another [group] of nice [wolves].

Figure 3. (**A**) Student biology teachers working with the worksheet in the face-to-face version of Activity 3. (**B**) One of the authors (Pablo Castillo) and a group of ninth-grade students discussed the problem raised in Activity 1.

stages of the cycle (activities), an environment of trust must be fostered that fosters interactions between participants, and where errors are perceived as opportunities to learn (Vosniadou, 2019).

○ Evaluation of Effectiveness

Based on our findings, we found that most students learn about natural selection (Cofré et al., 2018; Parraguez et al., in press), through this inquiry-based approach. Using one question from the Assessment of Contextual Reasoning about Natural Selection (ACORNS) (Nehm et al., 2012), before and after activities 2 and 3 in one ninth-grade class, the number of misconceptions (mostly need-based and chimerical explanations) decreased after the activities. On the other hand, students' use of natural selection elements (mutation, variation, fitness, and selective pressure) increased from before to after the activities (Table 2).

Table 2. The numbers of scientific concepts and misconceptions before and after Activities 2 and 3 in a ninth-grade class (Parraguez et al., in press). Amechanistic responses explain evolutionary change only because of comparative evidence (fossil, genetic, or morphological, not by a mechanism). A chimeric explanation states that new species originate from the reproduction of two preexisting and different species.

Student	Scientific Concepts before Activities	Misconceptions before Activities	Scientific Concepts after Activities	Misconceptions after Activities
S1	0	0	1 (variation)	0
S2	0	0	3 (variation, inheritance, fitness)	0
S3	0	1 (amechanistic)	1 (variation)	1 (need-based)
S4	0	0	2 (variation, inheritance)	0
S5	0	1 (need-based)	1 (variation)	1 (need-based)
S6	0	1 (need-based)	0	1 (need-based)
S7	0	1 (chimerical)	2 (variation, fitness)	0
S8	0	1 (chimerical)	3 (variation, inheritance, fitness)	0
S9	0	1 (need-based)	1 (variation)	0
S10	0	1 (need-based)	1 (selective pressure)	1 (need-based)

Concluding Remarks

Teaching evolution effectively is not an easy task. However, there are several approaches and strategies that can help us to work through, and eventually overcome, the intuitive explanations that students may hold about evolution. A first approach to achieving this objective seems to be to include data and real examples of evolution, and reflecting with the students on this evidence (Cofré et al., 2017, 2018), as in the different activities presented here. Teaching strategies where students share their ideas with their peers and manage to build their own conclusions about certain evolutionary phenomena appears to be one of the best ways. This time, we focus on the case of the origin of dogs to present three examples of activities with different dynamics, where argumentation, the use of models, and the incorporation of the NOS are used in an inquiry-based strategy. We use artificial selection to help students understand natural selection, as Darwin himself did by making an analogy between the two. Bringing evolution closer to students' everyday lives, such as with cases of domestication or diseases that we suffer from today, is an effective way to promote their interest in, and ultimately to help them understand, the content involved.

Supplemental Material

The following appendices are available with the online version of this article:

- Appendix S1: Summary of scientific information about dog evolution.
- Appendix S2: Worksheet for Activity 2 in Spanish and English.
- Appendix S3: Worksheet for Activity 3 in Spanish and English.

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References

Belyaev, D.K. (1979). Destabilizing selection as a factor in domestication. *Journal of Heredity*, *70*, 301–308.

Bergström, A., Frantz, L., Schmidt, R., Ersmark, E., Lebrasseur, O., et al. (2020). Origins and genetic legacy of prehistoric dogs. *Science*, *370*(6516), 557–64. https://www.science.org/doi/10.1126/science.aba9572.

Cofré, H., Cuevas, E. & Becerra, B. (2017). The relationship between biology teachers' understanding of the nature of science and the understanding and acceptance of the theory of evolution. *International Journal of Science Education*, *39*(16), 2243–60. https://www.tandfonline.com/doi/abs/10.1080/09500693.2017.1373410? journalCode=tsed20.

Cofré, H.L., Santibáñez, D.P., Jiménez, J.P., Spotorno, A., Carmona, F., et al. (2018). The effect of teaching the nature of science on students' acceptance and understanding of evolution: myth or reality? *Journal of Biological Education*, *52*(3), 248–61. https://www.tandfonline.com/doi/abs/10.1080/00219266.2017.1326968.

Dobzhansky, T. (1973). Nothing in biology makes sense except in the light of evolution. *American Biology Teacher*, *35*(3), 125–29. https://doi.org/10.2307/4444260.

Dugatkin, L.A. & Trut, L.N. (2017). *How to Tame a Fox (and Build a Dog)*. University of Chicago Press.

Funk, M. (Ed.). (2020). Research in *Science* journals. Ancient dog genomics: dog domestication was multifaceted. *Science*, *370*(6516), 545-C.

Glaze, A.L. (2018) Book Reviews. *How to Tame a Fox (and Build a Dog)*. *American Biology Teacher*, *80*(7), 546.

Glaze, A.L. & Goldston, M.J. (2015). US science teaching and learning of evolution: a critical review of literature 2000–2014. *Science Education*, *99*(3), 500–518.

Harms, U. & Reiss, M.J. (Eds). (2019). *Evolution Education Re-considered: Understanding What Works*. Springer.

Hodson, J. (2019) A Simplified Bioenergetics Model of a Hammerhead Shark for Teaching Natural Selection. *American Biology Teacher*, *81*(2), 115–19.

Kaminski, J., Waller, B.M., Diogo, R., Hartstone-Rose, A. & Burrows, A.M. (2019). Evolution of facial muscle anatomy in dogs. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(29), 14677–81. https://www.pnas.org/content/116/29/14677.

Kampourakis, K. (2014). *Understanding Evolution*. Cambridge University Press.

Karplus, R. (1977). Science teaching and the development of reasoning. *Journal of Research in Science Teaching*, *14*(2), 169–75.

Lucci, K. & Cooper, R.A. (2019). Using the I^2 strategy to help students think like biologists about natural selection. *American Biology Teacher*, *81*(2), 88–95. https://doi.org/10.1525/abt.2019.81.2.88.

Malone, K.L., Schuchardt, A.M. & Sabree, Z. (2019). Models and modelling in evolution. In U. Harms & M.J. Reiss (Eds.), *Evolution Education Re-considered: Understanding What Works* (pp. 207–26). Springer.

McComas, W. (2018). The nature of science and the next generation of biology education. *American Biology Teacher*, *77*(7), 485–91.

Nehm, R.H., Beggrow, E.P., Opfer, J.E. & Ha, M. (2012). Reasoning about natural selection: diagnosing contextual competency using the ACORNS instrument. *American Biology Teacher*, *74*(2), 92–98. https://doi.org/10.1525/abt.2012.74.2.6.

Nehm, R.H. & Kampourakis, K. (2016). Conceptual Change in Science and Science Education. In M. Peters, (Ed.), *Encyclopedia of Educational Philosophy and Theory*. Springer. https://doi.org/10.1007/978-981-287-532-7_41 -1.

Osborne, J., Donovan, B.M., Henderson, J.B., MacPherson, A.C. & Wild, A. (2017). *Arguing from Evidence in Middle School Science: 24 Activities for Productive Talk and Deeper Learning*. Corwin.

Pavlidis, P. & Somel, M. (2020). Of dogs and men. *Science*, *370*(6516), 522–23. https://www.science.org/doi/10.1126/science.abe7823.

Parraguez, C., Núñez, P., Krüger, D. & Cofré, H.L. (in press). Describing changes in student thinking about evolution in response to instruction: The case of a group of Chilean ninth-grade students. *Journal of Biological Education*. https://doi.org/10.1080/00219266.2021.2009006.

Pobiner, B., Watson, W., Beardsley, P. & Bertka, C. (2018). Using human example to teach evolution to high school students: increasing understanding and decreasing cognitive biases and misconceptions. In U. Harms & M.J. Reiss (Eds), *Evolution Education Re-considered: Understanding What Works* (pp. 185–205). Springer.

Scharmann, L.C. (2018). Evolution and nature of science instruction. *Evolution Education & Outreach*, *11*,14.

Sinatra, G.M., Brem, S. K. & Evans, E.M. (2008). Changing minds? Implications of conceptual change for teaching and learning about biological evolution. *Evolution: Education and Outreach*, *1*, 189–95.

Trut, L. & Dugatkin, L. (2017). Wild foxes can be transformed into pets in a few generations. *Scientific American*.

Vosniadou, S. (2019). The development of students' understanding of science. *Frontiers in Education*, *4*(32). https://www.frontiersin.org/article/10.3389/feduc.2019.00032.

Williams, M.A., Friedrichsen, P.J., Sadler, T.D. & Brown, P.J.B. (2018). Modeling the emergence of antibiotic resistance in bacterial populations. *American Biology Teacher*, *80*(3), 210–16. https://doi.org/10.1525/abt.2018.80.3.214.

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TIPS, TRICKS & TECHNIQUES

Explore Paleoanthropology Fieldwork: A Virtual Expedition to Rising Star Cave (South Africa) with DinalediVR

ANDREW MONTGOMERY AND BECCA PEIXOTTO

Abstract

This classroom exercise utilizes a free mobile virtual reality app to introduce students to (1) the process by which paleoanthropologists find and interpret fossils, (2) the importance of two recent hominin fossil finds in the Cradle of Humankind of South Africa, and (3) the variety of science careers that contribute to paleoanthropological research. Before their virtual field trip, learners are introduced to the Homo naledi *and* Australopithecus *sediba discoveries and to some of the researchers from the team through a collection of online resources. In the app, learners explore and find fossils in the Dinaledi Chamber of Rising Star Cave in South Africa, where the first fossils of* H. naledi *were found. Postexploration analysis and reflection prompts encourage learners to consider how researchers decide how and where to excavate, which skills are needed to study our human origins, and why this research is important.*

Key Words: *virtual reality; Homo naledi; paleoanthropology; exploration; discovery; hominin; fossils; excavation; research.*

○ Introduction

Paleoanthropology, broadly defined as the study of our human origins, can be a daunting topic to broach in the classroom, but it can also be an engaging means by which students master key concepts in biology. Although often omitted from state science standards (Watts et al., 2016; Vasquez, 2017), educators can utilize human evolution to illustrate scientific method and process for learners of all ages. The DinalediVR app offers an introduction to field paleoanthropology and to the diversity of skill sets needed on paleoanthropology research teams. This activity consists of three parts: preexploration research, virtual field work, and postexploration analysis or reflection. Supplemental resources for this activity can be found on the Perot Museum of Nature and Science website (http://perotmuseum.org/DinalediVR).

Virtual reality (VR) can be an effective teaching tool for learners from primary school to university, allowing learners to embody different experiences, simulate dangerous experiments or distant places, and manipulate objects they would ordinarily not be allowed to handle (see, for example, Bailey and Bailenson, 2017; Bailenson et al., 2008; Ellenberger, 2017).

○ DinalediVR Background

The Cradle of Humankind is a UNESCO World Heritage site in South Africa known for its vast networks of caves that preserve fossils representing at least 2.5 million years of hominid evolution. There, in 2013, a team of cavers and archaeologists descended into the Rising Star Cave, passing through a narrow fissure 30 meters underground to enter the Dinaledi Chamber where they excavated fossils of an approximately 250,000-year-old hominin, ***Homo naledi*** (Dirks et al., 2017). DinalediVR, a virtual reality app, brings the story of the discovery and our ancient relative to life in an interactive way and features narration by project scientists in six languages. Reconstructed from laser scans and photographs, the virtual space is populated with 3D renderings of fossils attributed to ***H. naledi***, which users can pick up. An untimed, unnarrated Free Play mode allows users to explore the chamber at their own pace. DinalediVR introduces learners to paleoanthropology through themes of exploration and discovery and is intended to supplement other classroom instruction in evolution, archaeology, or scientific process.

○ The Activity

What You Need

To experience DinalediVR in 3D as immersive virtual reality, learners will need

- An iOS or Android smartphone or tablet with the app installed
    - Once downloaded, the app does not require internet access.
- VR viewers

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    - The app is designed for low-cost Google Cardboard–compatible viewers but works on other head-mounted devices as well. It can be used without a viewer or on a shared flat screen in monoscopic mode.
- A place to sit
    - We strongly advise against walking around in the physical world while exploring the virtual space. Swivel chairs allow users to rotate in 360 degrees and reduce the risk of collisions or falls.
- Headphones (optional)

Studies of immersive VR in educational contexts suggest learners' experience—or lack of experience—with the technology has an impact on the effectiveness of VR as an educational tool (Markowitz et al., 2018). We recommend either allowing learners to practice with another VR experience prior to entering DinalediVR or encouraging them to explore the cave more than once.

Part 1: Preexploration Research

DinalediVR can be used on its own, but the plan presented here is designed as a miniexpedition. Background research helps paleoanthropologists prepare for field exploration and excavation. Before using the app, students should become familiar with both paleoanthropology and the expedition to Rising Star Cave. A few basic facts about the location of the cave, its significance, and the fossils themselves can be found on a one-page Instructions Card (Figure 1) available on the DinalediVR companion website (https://www.perotmuseum.org/dinaledivr). The website also includes FAQs, scientist profiles, links to articles, videos, and other supplemental materials, including sample lesson plans (and a place for teachers to share their own lesson plans).

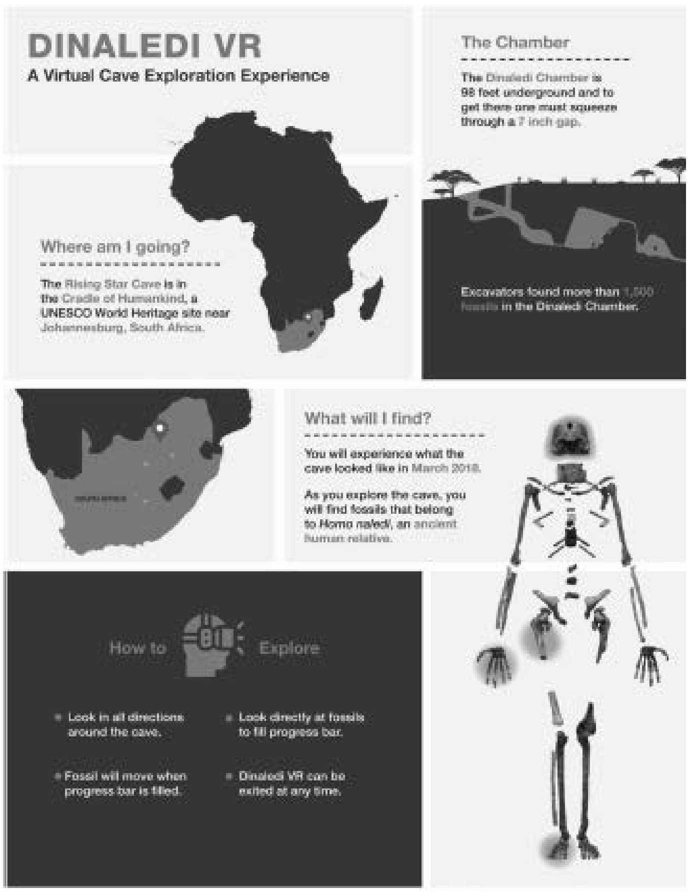

Figure 1. DinalediVR Instruction Card.

Additional learner-friendly background information about the discoveries, Pleistocene environment, characteristics, and analysis of *H. naledi* and another South African hominin, ***Australopithecus sediba,*** can be found in the online companion to the *Origins: Fossils from the Cradle of Humankind* exhibit (https://origins.perotmuseum.org), which was on display at the Perot Museum of Nature and Science from October 2019 to March 2020. Special attention is given to the diverse teams who contribute to the ongoing research in South Africa. The online exhibit can be used with either Part 1 of the miniexpedition to familiarize learners with the topic or Part 3 (Postexploration Analysis) to demonstrate one way field discoveries are presented to the public.

Once students are familiar with the project and subject matter, they are ready to explore DinalediVR.

Part 2: Exploration & Discovery

To use the app, make sure the DinalediVR app is downloaded on your device. It is available for free from both the Google Play and Apple stores.

Before going underground, users are prompted to select a language, choosing from English, EU Spanish, Mexican Spanish, isiZulu, Sesotho and Setswana. The virtual adventure begins with a fly-in from above the Earth down to the Cradle of Humankind UNESCO World Heritage Site in South Africa. After a brief moment of darkness, your headlamp turns on, revealing the Dinaledi Chamber of the Rising Star Cave, and a member of the research team talks to you in the language you selected. The audio describes the journey to the cave, the significance of the site, and the excavation. Although captioning is not provided within the app, transcripts in several languages are available on the website.

While in the virtual Dinaledi Chamber, users are positioned next to the Puzzle Box, an area less than $1m^2$, from which the team excavated nearly 1000 hominin fossil fragments in 2013–2014. Users have the opportunity to "find" five fossils: the composite reconstructed skull of *H. naledi*, a fragment of a thigh bone (proximal femur), a reconstructed hand, a reconstructed foot, and a lower jaw (mandible). The 3D fossil models are drawn from Morphosource (https://www.morphosource.org) and represent skeletal elements actually recovered from the excavation depicted in the app (their locations have been adjusted to make the user interface easier). Users "pick up" fossils by holding their gaze on a bone until a progress bar fills up. The fossil will then come into the center of the frame and rotate for a few seconds before returning to its place.

The narration also prompts users to look around the cave to see speleothems on the ceiling, and the narrow hallway that leads to the entrance. A bat can be seen clinging to a rock formation before it flies away.

In the narrated version, the light begins to flicker after approximately two and a half minutes and a menu screen appears with choices to begin again, enter Free Play mode, visit the website, or share on social media. Free Play mode continues until the user gazes at the Exit sign long enough for the progress bar to fill.

Part 3: Postexploration Analysis & Reflection

Excavating new fossils is exciting, but postexploration analysis and reflection helps paleoanthropologists learn even more about what their field finds. Learners can practice this important step of the fieldwork process through written responses or small group discussions on one or more of the following prompts on the themes of exploration, discovery, and collaboration.

- ***Exploration.*** Finding a fossil is sometimes like finding a needle in a haystack, yet paleoanthropologists are still able to find new hominin fossils each year. How do they decide where they should look? After learning about the discovery of *H. naledi*, where do you think that the researchers should look next? What training/mindset does one need to venture into remote places like the Dinaledi Chamber? Why do people do this?
- ***Discovery.*** What did you notice about the way that the excavation area was set up? What strategy do you think paleoanthropologists have for excavating fossils? What do discoveries like fossils of *H. naledi* tell us about our past, present and future? How are the fossils of *H. naledi* similar to or different from your own bones? What evidence would you look for to determine how the bones got into the cave?
- ***Collaboration.*** In your preexploration research, you learned that the team includes people with various backgrounds and specialties who all contribute to discoveries in the field, in the lab, and in museums. Make a list of specialties that team members bring to the study of the Dinaledi Chamber and to the creation of DinalediVR. How does this diversity benefit the science? What skills do you have that you think could be useful for a project like this one?

○ Conclusion

Many resources are available to assist educators as they teach their students about our shared human origins, including those found on the DinalediVR website (https://www.perotmuseum.org/dinaledivr). VR offers a way to bring paleoanthropological science to life, particularly for learners in remote or low-income areas whose access to museums is limited. The DinalediVR app can be used with nearly all grade levels and is easily adaptable to both in-person classroom and remote or online learning situations. The app was designed to spark interest in paleoanthropology and to inspire learners to think of themselves as scientific explorers.

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References

Bailenson, J.N., Yee, N., Blascovich, J., Beall, A.C., Lundblad, N. & Jin, M. (2008). The use of immersive virtual reality in the learning sciences: digital transformations of teachers, students, and social context. *Journal of the Learning Sciences*, *17*(1), 102–41.

Bailey, J.O. & Bailenson, J.N. (2017). Immersive virtual reality and the developing child. In Fran C. Blumber and P.J. Brooks (Eds.). *Cognitive Development in Digital Contexts* (pp. 181–200), Academic Press.

Dirks, P.H.G.M., Roberts, E.M., Hilbert-Wolf, H., Kramers, J.D., Hawks, J., et al. (2017). The age of *Homo naledi* and associated sediments in the Rising Star Cave, South Africa. *eLife*, *6*, e24321. https://doi.org/10.7554/eLife.24231.

Ellenberger, K. (2017). Virtual and augmented reality in public archaeology teaching. *Advances in Archaeological Practice*, *5*(3), 305–309. https://doi.org/10.1017/aap.2017.20.

Vasquez, B. (2017). A state-by-state comparison of middle school science standards on evolution in the United States. *Evolution: Education and Outreach*, *10*, 5.

Watts, E., Levit, G., and Hossfeld, U. (2016). Science standards: the foundation of evolution education in the United States. *Perspectives in Science*, *10*, 59–65. https://doi.org/10.1016/j.pisc.2016.08.004.

ANDREW MONTGOMERY was the inaugural Science Communication Fellow, and BECCA PEIXOTTO was curator of the *Origins: Fossils from the Cradle of Humankind* exhibit at the Center for the Exploration of the Human Journey, Perot Museum of Nature and Science, Dallas, TX 75201. E-mail: beccapeixotto@gmail.com.

TIPS, TRICKS & TECHNIQUES

Getting More out of Less: Designing Short Homework Assignments That Focus on Application & Analysis

JULIE MINBIOLE, STEPHEN TRAPHAGEN

Abstract

Homework is an integral component of most science courses but can have an impact on student learning only when students actually complete the assignment. Low completion rate of homework, then, is an impediment to student success in science courses, and a source of frustration for instructor and students alike. Here, we outline a set of design principles supported by research in how students learn, intended to streamline outside-of-class assignments to address course goals, improve student buy-in and motivation, and provide instructors better formative assessment data. We also share examples of outside-of-class assignments aligned to these principles to aid instructors in shortening and focusing the homework they choose to assign in their courses.

Key Words: *Homework; instructional practices; formative assessment; motivation; engagement.*

○ Introduction

Ask any high school or college instructor to list their gripes about students' work, and "low homework completion" or "lack of preparedness for class" are bound to be near the top. There will certainly never be one magic-bullet solution to this problem, but a contributing factor may be the nature of homework. In this paper, we briefly examine the research in homework efficacy to make the argument that homework that is intentionally designed to be focused tightly on one or two instructional or assessment goals increases homework completion rates, student engagement, and course coherence.

In our classes, we have used homework for a variety of purposes, and we are not alone—research on homework effectiveness cites many common purposes for homework (Blazer, 2009). These include reinforcing course material, acquired skills practice, preparation for upcoming class work, application of knowledge, extension of class material, and "covering more" material / responding to semester- and year-long curricular constraints. In choosing the tasks we ask students to complete, and the goals we're attempting to advance, "teachers not only assign homework, they *design* homework," reflecting our understanding and priorities for "the skills, abilities, and needs of their students, and the characteristics and situations of their students' families" (Epstein & Van Voorhis, 2001).

Even if every student completed 100% of their homework in a particular course, it seems unlikely that homework assignments would be able to successfully accomplish such a broad range of academic and social tasks—so how do we know if our students are being successful? How do we know that our homework assignments are contributing to student success? More troubling, how would students know that their work is contributing to their success in the course and is thus academically or personally meaningful? The first two questions speak to course design and implications on student learning, and the third speaks to student motivation and engagement. In our classes, redesigning homework assignments has not only helped students (as evidenced by homework completion rates and student evaluations) but also provided timely formative assessment data that has helped us as instructors to improve course coherence as we move through a unit of instruction (Minbiole, 2016).

○ Design Principles

With a concept as broad as homework, encompassing a wide variety of outside-of-class tasks assigned K–16, drawing conclusions from any single literature review may be problematic. In fact, this conflict in priorities and conclusions about efficacy of homework has itself been the subject of literature review. It is striking that, in the roughly 100 years that homework has been studied in the US, there is no conclusive body of evidence that it "works" broadly—meaning that it is associated with significant gains in student performance, absent other factors (Eren & Henderson, 2011). There does seem to be consensus around a few design principles. Homework is more effective when the task is high impact, when the assignment is completed, and when it leads to timely feedback.

High impact tasks are characterized by application of concepts (rather than lower-level thinking tasks), direct links to in-class work, and a student perception of achievement on completion

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(in other words, tasks that students find inherently meaningful)—this improves student ownership of coursework, and thus agency and motivation in the course (Akasheh et al., 2012; Bransford et al., 2000; Marzano et al., 2001).

Completion of tasks is improved when their length gives students a meaningful perception of achievement on a task (Svinicki, 2004) and are sufficiently short that work is "distributed in small doses" (Passow et al., 2006). It should go without saying, but homework can have a high impact on student learning only when students actually complete the assignment. Feelings of achievement, on assignments of manageable length, make the homework feel integral to the course rather than "extra" or "busywork" (Bembenutty, 2009).

Timely feedback means that students get information about their specific performance or understanding, in time to "modify his or her thinking or behavior to improve learning" on a topic (Shute, 2008). This meaningful feedback from the instructor—made possible by the shorter length of assignment, helps students make adjustments key to greater success in the course, while also providing the instructor with formative assessment data in time to make instructional changes based on student misconceptions. Note: "timely feedback" does not exclusively mean returning marked papers with comments—it can take the form of instructional changes or class discussion based on homework performance, as described ahead (Chappuis, 2014; Ruiz-Primo & Furtak, 2007).

○ Application: What This Looks Like in Our Classes

Shorter Problem Sets, with In-Class Discussion Procedures

In Julie's genetics class, problem-set homework assignments have been shortened to one to two highly engaging problems, covering critical concepts or skills in the course. Students are expected to come to the next class meeting with the problem set complete to the best of their ability, but they are also given the first 10 minutes of class to discuss the work in pairs or small groups. This time serves several purposes: student talk provides valuable formative assessment data to the instructor, ties outside-of-class work to class activities, makes students responsible for evaluating each other's understandings, and reinforces the habit of completing work. In our experience, 10 minutes is enough time for a student who made an honest attempt but needed clarification on a misconception to complete the assignment, but it is not useful for a student who has not attempted the homework to rush through a substantial response. High impact is achieved by distilling the task down to a two-problem set that requires understanding of multiple genetics concepts in order to fully execute the task. The manageable size of the assignment allows for completion of the task in a very reasonable amount of time outside of class, while the in-person discussion component allows students to receive real-time feedback and provides a sense of achievement as they refine and improve their answers as a group without relying solely on instructor feedback.

Building Formative Assessment into Flipped-Class Videos with TED-Ed

Using instructional videos as homework (the Flipped Classroom model) has become a popular method to move direct instruction out of face-to-face synchronous class time, making more room for lab and discussion, like in the collaborative homework debrief discussed previously (Heyborne & Perrett, 2016). In a traditional in-class lecture, students often complete clicker questions or exit tickets to check for understanding. The limitation of these strategies, though, is that the instructor cannot act on this assessment and make adjustments until the next class meeting. However, once students are consuming material between classes that might otherwise be a face-to-face lecture, it creates an opportunity for formative assessment to inform instruction before the start of class—essentially, students are completing entrance tickets rather than exit tickets. The TED-Ed platform provides tools to add multiple-choice and short-answer questions to any online video, and student submissions are viewable online or in an LMS such as Canvas. Additionally, the platform contains a library of highly engaging videos, or can be used with any video available on YouTube (including instructor-created videos). This creates a homework assignment that contains both the instructional video for students and questions on key concepts—letting the instructor check for student understanding before the next class meeting. In Julie's class, TED-Ed videos are selected for key concepts, when textbook readings or static figures are inadequate. Delivering this material in video form gives students "the power of the pause button," allowing them to process the material without the extemporaneous pressure of an in-class lecture. Additionally, starting class discussing key ideas from the TED-Ed and addressing misconceptions has improved student understanding (measured by quiz scores) and engagement (these assignments are highlighted in course evaluations). The single-concept, engaging videos are high impact, and the short format increases the likelihood students will complete the task. The digital format allows instructors to grade the assessment quickly and provide timely feedback and/or course modifications to address student misconceptions before proceeding to additional course content.

Modifying Existing Homework Assignments to "Get More out of Less"

Not every assignment must be designed from scratch; the reality is we all have existing assignments aligned to our course goals. If low homework completion is an impediment to class functioning, it may make sense to look at existing assignments and pare down according to course and student learning priorities. The principles in Understanding by Design offer guidance by characterizing course learning goals into "essential," "highly desirable," and "desirable" elements (Wiggins & McTighe, 2005). To leverage out-of-class activities to improve student understanding, consider moving away from assigning/assessing multiple priorities in the same assignment and instead leverage interesting examples as hooks to assess essential course elements. To shorten assignments and improve student completion, the instructional challenge becomes, "What is the one thing I want students to take away from this topic?" Asking one or two questions that require application of concepts for a single understanding increases impact. This practice of focusing improves completion rates, gives the instructor clearer formative assessment, and gives time back to all stakeholders in the course—instructor and students alike.

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References

Akasheh, F., Echempati, R. & Sala, A.L. (2012). *Assessment of Student Learning through Homework Intervention Method.* Paper presented at the 2012 ASEE Annual Conference & Exposition, San Antonio, TX.

Bembenutty, H. (2009). Self-regulation of homework completion. *Psychology, 6*(4), 138–53.

Bransford, J.D., Brown, A.L. & Cocking, R.R. (Eds.). (2000). *How People Learn: Brain, Mind, Experience, and School* (expanded edition). National Academies Press.

Chappuis, J. (2014). *Seven Strategies of Assessment for Learning* (2nd ed.). Pearson.

Epstein, J.L. & Van Voorhis, F.L. (2001). More than minutes: teachers' roles in designing homework. *Educational Psychologist, 36*(3), 181–93. https://doi.org/10.1207/S15326985EP3603_4.

Eren, O. & Henderson, D.J. (2011). Are we wasting our children's time by giving them more homework?. *Economics of Education Review, 30*(5), 950–61.

Heyborne, W.H. & Perrett, J.J. (2016). To flip or not to flip? Analysis of a flipped classroom pedagogy in a general biology course. *Journal of College Science Teaching, 45*(4).

Marzano, R.J., Pickering, D.J. & Pollock, J.E. (2001). Classroom instruction that works: research-based strategies for increasing student achievement.

Minbiole, J. (2016). Improving course coherence and assessment rigor: "understanding by design" in a nonmajors biology course. *American Biology Teacher, 78*(6), 463–70. https://doi.org/10.1525/abt.2016.78.6.463.

Passow, H.J., Mayhew, M.J., Finelli, C.J., Harding, T.S. & Carpenter, D.D. (2006). Factors influencing engineering students' decisions to cheat by type of assessment. *Research in Higher Education, 47*(6), 643–84. https://doi.org/10.1007/s11162-006-9010-y.

Ruiz-Primo, M.A. & Furtak, E.M. (2007). Exploring teachers' informal formative assessment practices and students' understanding in the context of scientific inquiry. *Journal of Research in Science Teaching, 44*(1), 57–84. https://doi.org/10.1002/tea.20163.

Shute, V.J. (2008). Focus on formative feedback. *Review of Educational Research, 78*(1), 153–89.

Svinicki, M.D. (2004). *Learning and Motivation in the Postsecondary Classroom*. Anker.

Wiggins, G. & McTighe, J. (2005). *Understanding by Design*. Association for Supervision and Curriculum Development.

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TIPS, TRICKS & TECHNIQUES

Virtual Reality: Flight of Fancy or Feasible? Ways to Use Virtual Reality Technologies to Enhance Students' Science Learning

REBECCA HITE

Abstract

Virtual Reality (VR) is an emerging technology that provides K–12 students with unique experiences for robust science learning by transporting them to a virtual world where they may engage directly with scientific phenomena. This is because VR creates lifelike three-dimensional spaces where students can manipulate objects; hear, see, and sometimes feel the environment; and explore places that mimic attributes of the real world. VR holds great utility in science education by engaging students in science topics that may be otherwise inaccessible to them in the real world. This inaccessibility may stem from the content (being too small, large, or abstract), safety issues (too hazardous or dangerous), not having access to the materials in their context, possessing physical or cognitive disabilities where they need to do the activity repeatedly or differently, or having cultural, religious, or ethical concerns related to conducting specific science experiments. This commentary discusses how three key types of VR hardware (VR viewers, desktop VR systems, and head-mounted displays) can be incorporated into science standards, curriculum, and instruction by delineating the pros and cons of each. The commentary concludes with specific, stepwise guidance in ideating, designing, and implementing VR-based experiences for K–12 students in the science classroom.

Key Words: *Curriculum; instruction; virtual presence; virtual reality.*

○ Introduction

American science classrooms have changed with the incorporation of new and varied technologies for science learning. Advancing processing speeds coupled with reduced costs have led to a new era of technology-enhanced instruction in K–12 classrooms. Today, districts and schools are now incorporating cutting-edge emerging technologies into the array of instructional tools available to K–12 teachers of science. Emerging technologies are defined as new technologies with an immense potential for impacts on communication, business, and education (Rotolo et al., 2015) like artificial intelligence, the internet of things, nanotechnologies, robotics, and virtual reality. Virtual reality (VR) has captured the attention of children and adults alike in in its ability to seemingly transport one into a realistic alternative dimension where you can interact with objects and explore places in an immersive virtual world. This ability to transcend worlds may help to explain VR's popularity in mainstream culture, health care, tourism, video games, and now, science classrooms.

The magic of VR lies in its ability to induce *virtual presence*, or the sensation that you are really there—immersed within and interacting with the virtual realm (Sheridan, 1992). Virtual presence occurs when you are able to control and interact with virtual objects that look, feel, and behave like the real thing. Your VR experience is accurately mimicking the sights, sounds, and sensations of the real world in a way that "feels real." Virtual presence has been shown to be a factor in science learning, as students can experience unique ways to interact with scientific phenomena that is generally inaccessible in the real world (Hite, 2016). This notion of inaccessibility is important to when and why VR can be a useful tool to help students learn science.

○ How VR-Enhanced Instruction Can Help Students Learn Science

Generally, VR is a viable option for science learning when the real world is inaccessible. Given that the real world is ideal for gaining knowledge or practicing a skill, this option may not be accessible to or safe for the learner. VR has been used in higher and vocational education for training when the real world is too dangerous or hazardous, like applying a medical procedure for the first time on a live subject. This can also extend to the classroom as there are science experiments that are safer to conduct in VR. Examples include culturing bacterial cells or modeling viral spread. Since these experiments are generative for students' development of science knowledge and skills, VR provides a safe yet viable alternative.

However, there are other aspects of inaccessibility to consider that VR can help to alleviate. VR can help students access scientific phenomena that are too small, in the past, or into the future. For example, students can view how microscopic macromolecules

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aggregated on early Earth to form coacervates or how increasing temperatures will impact Earth's ecosystems in the near future. Other aspects of inaccessibility include cost and capital. It may be cost prohibitive to engage in certain activities with supplies that are limited, complications (such as need for high amounts of scaffolding), or need for repetition to gain proficiency. In these cases, VR can provide all the materials and on-demand information within the Virtual Learning Environment (VLE) and reset the experiment for repeat trials. Notably VR can provide a more equitable science learning experience for students who are chronically absent or who may need remediation or enrichment. Also, for students who have religious, cultural, or ethical concerns toward dissection, VR provides a high-quality alternative to access the vital science knowledge and skills derived from participation in dissection activities.

○ Key Strategies for Determining When to Incorporate VR into the Curriculum

Start with your state's science standards or the Next Generation Science Standards (NGSS). Decide which topics within the standards are currently inaccessible to your learners or may be enhanced by VR. Next, consider what activities from those topics that may be too dangerous, hazardous, small, abstract, costly, complicated, or disconcerting for your learners. Developing this list will help inform your next step, which is to review the major types of VR hardware and software available for science learning.

○ Three Major Types of Virtual Reality Hardware

There are three major types of VR hardware used in K–12 science education: VR viewers, desktop VR systems, and head-mounted displays (see Hite et al., 2019). Each type of technology has pros and cons (see Figure 1) when used in the science classroom.

VR Viewers

VR viewers use a set of polarized lenses to create a visual three-dimensional (3D) effect. Students turn their head to have a 3D screen follow their movements and use a small button on the upper left to interact with the VLE. One application useful to science education is a virtual field trip of Berlin's *für Naturkunde* Natural History Museum on *Google Expeditions*. Using Google Cardboard 3D viewers, students can tour the Earth's rich biodiversity and learn about preservation strategies to mitigate species loss.

Pros. A VR viewer can be made from simple materials found at home (e.g., cardboard, magnets, fasteners, and rubber bands) and a one-time purchase of lenses (around $3 each). The major hardware cost is procuring a VR-enabled device, like a late-generation smartphone, which is needed to place inside the viewer to runs specialized VR software applications (known as apps). Many of these apps are free for download and educational use.

Cons. However, many VR viewer apps tend to cover niche subjects, so there may not be a high-quality app for the curriculum topic you need. Other cons of viewers are they are nondurable and cumbersome when used for long periods of time. This may cause a certain type of discomfort known as VR sickness, when individuals experience wooziness due to sensory inputs (Kim et al., 2018). Last, but not least, users' perceptions of virtual presence may be poor as students can be easily distracted by the outside environment, have limited abilities (e.g., the sole means of interaction is through a single button) to interact within the VLE, and have reduced sensory engagement.

Desktop Systems

Desktop-based VR systems use a modified desktop (or laptop) computer with head-tracking sensors that map to dots on polarized eyewear. Desktop systems use a mouse or a stylus pen for the user to more fully interact (for virtual presence) within the virtual world. *Newton's Park* by zSpace provides a virtual physics playground where students can test how various forces (e.g., gravity and friction) compare from Earth to the moon and the other known planets in our solar system by toggling features and experimenting with 3D objects.

Pros. Desktop systems use elements (e.g., eyewear, stylus) that are familiar to students so they don't feel as confined by the technology itself (Hite et al., 2019). Also, there are many apps available for K–12 students that use tools like Unity 3D for independent app development.

Cons. Desktop systems are more costly than VR viewers because they require purchase of specialized hardware and often software. However, when not in VR mode, desktop systems operate as a standard personal computer, ideal for school settings.

Head-Mounted Displays

Head-mounted displays (HMDs) are commonly found in video gaming and industry. Unlike desktop systems, the user is more fully engaged in the virtual world (sensory immersion) and is able to interact by using some form of joystick or glove for more naturalistic hand motions. *Breaking Boundaries in Science* is an Oculus app that allows students to relive the famous discoveries of three women scientists: Jane Goodall, Marie Curie, and Grace Hopper. Voiced by Jane Goodall herself, students explore immersive vignettes of the lived experiences of these women in their historic and scientific endeavors.

Pros. HMDs have a wide array of hardware and software options. Given that they are able to produce a robust sense of virtual presence, they may be useful for robust science learning.

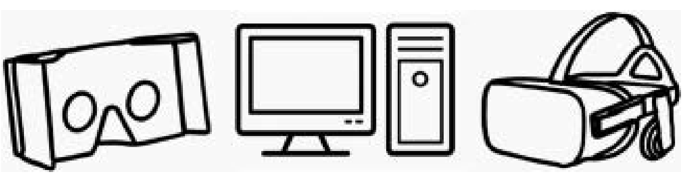

Figure 1. Three types of VR hardware: VR viewers, desktop systems, and head-mounted displays.

Cons. HMDs are expensive ($500) and unlike desktop VR can only used for VR-based applications. One of the cons of HMDs is its greatest strength, which is its ability to induce virtual presence. Virtual worlds may become too real for certain users and induce what is known as *VR phobia*, a sense of fear or belief that what is occurring in the VLE is happening to them in real life. This robust sense of virtual presence is why VR has been used as an effective means of exposure therapy for phobia treatment (Park et al., 2019), yet VR phobia can be a real concern for K–12 learners.

○ Key Strategies for How to Incorporate VR into Your Instruction

So, when you are ready to use VR in your biology teaching, make sure to ask yourself the following questions for successful implementation:

- Which science topics (standards) would be best suited to VR-assisted instruction?
- Which VR hardware has the best apps for those topics selected from the standards?
- Which type of VR hardware is best suited for my students? (Consider which type is easiest or most intuitive for them to use, which is less likely to break due to rough handling or induce VR sickness or VR phobia.)
- Which type of VR hardware (and software) is best suited to my budget?
- How much class time should I dedicate to help students learn how to use the technology?
- How much class time should I dedicated to having students use the technology to learn?
- How will I use the VR to support their learning. (Consider if you want to start your students with a VR-based experience and then real world experience, or vice versa.)
- What is my plan if a student becomes VR sick or VR phobic?
- How can I design assessments that take into account the 3D nature of the technology to assess the learning they have gained from using VR for science learning?

Technology-enhanced instruction has the ability to supplement your science instruction. By leveraging these tools in thoughtful and specific ways, your students can have a greater variety of science experiences for greater science learning.

References

Hite, R. (2016). *Perceptions of Virtual Presence in 3-D, Haptic-Enabled, Virtual Reality Instruction.* PhD dissertation, North Carolina State University.

Hite, R., Childers, G. & Jones, M.G. (2019). Review of virtual reality hardware employed in K-20 science education. In A. Zhang & D. Cristol (Eds.), *Handbook of Mobile Teaching and Learning* (2nd ed., pp. 1–12). Springer.

Hite, R., Jones, M.G., Childers, G., Chesnutt, K., Corin, E.N. & Pereyra, M. (2019). Teachers' pedagogical acceptance of novel 3D, haptic-enabled, virtual reality technology. *Electronic Journal of Science Education*, 23(1), 1–34.

Kim, H.K., Park, J., Choi, Y. & Choe, M. (2018). Virtual reality sickness questionnaire (VRSQ): motion sickness measurement index in a virtual reality environment. *Applied ergonomics*, *69*, 66–73.

Park, M.J., Kim, D.J., Lee, U., Na, E.J. & Jeon, H.J. (2019). A literature overview of virtual reality (VR) in treatment of psychiatric disorders: recent advances and limitations. *Frontiers in Psychiatry*, *10*. https://doi.org/10.3389/fpsyt.2019.00505.

Rotolo, D., Hicks, D. & Martin, B.R. (2015). What is an emerging technology?. *Research policy*, *44*(10), 1827–43.

Sheridan, T.B. (1992). Musings on telepresence and virtual presence. *Presence: Teleoperators & Virtual Environments*, *1*(1), 120–126.

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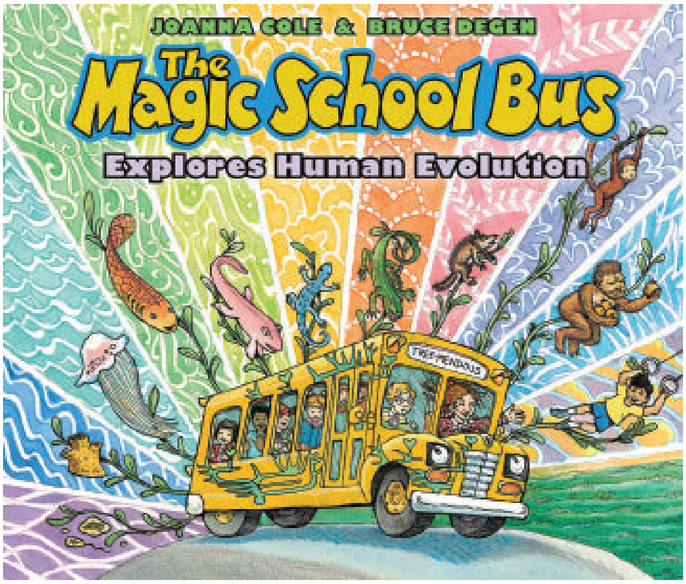
The mission of the NABT BioClub is to recruit, support, nurture, and promote students who have an interest in biological sciences for personal reasons, academic preparation, the betterment of society, and possible career opportunities by providing guidance, resources, and activities to meet these goals.

Look for the BioClub logo to indicate recommended articles for NABT BioClub members. If you are interested in forming a chapter of the NABT BioClub, contact NABT at office@nabt.org.

BOOK REVIEW

AMANDA L. GLAZE, DEPARTMENT EDITOR



The Magic School Bus Explores Human Evolution. By Joanna Cole and Bruce Degen. 2021. Scholastic Press. (ISBN 9780590108287.) 56 pp. Hardcover. $17.99.

It's the longest field trip ever for Ms. Frizzle's class! In the latest installment in the popular *Magic School Bus* series, a classroom activity involving the construction of family trees leads to a 3.5-billion-year excursion, tracing the human lineage from the primordial cell through the first vertebrates to mammals, primates, hominins, and, finally, *Homo sapiens*. "We may speak different languages, eat different food, make different art, and have different religions," Ms. Frizzle observes toward the end of the journey. "But we are all human beings with the same family tree" (p. 45). (The message is reinforced by the inclusion on the field trip of a cousin of one of the students, visiting from China.) The students then work together to construct a "terrific"—and charming, if selective—phylogenetic chart.

The approach of beginning with the familiar idea of a family tree and then introducing the idea of common ancestry is ideal for the intended readers, four through eight years old. The focus on following the human lineage is likely to reinforce the misconception that evolution is intrinsically progressive, which the occasional digression to highlight different lineages is not likely to be able to dispel, but the advantages outweigh the disadvantages. As in the *Magic School Bus* series in general, the pages (attractively illustrated by Bruce Degen) teem with corny jokes both verbal and visual, informative sidebars, and cameo appearances that invite further exploration—paleontology aficionados will particularly relish the opportunity to tell young readers about *Pikaia*, *Tiktaalik*, and gorgonopsids.

The last few pages abandon the narrative approach for straightforward exposition, and here especially the young reader will need further information and explanation from a well-informed mentor. (It would have been nice for there to be a guide for teachers and parents to prepare them for these discussions.) The exposition begins with a sketch of the evidence for evolution, including the fossil record and its documentation of evolutionary transitions, anatomical homology (misleadingly labeled "body plans"), embryological homology, a gesture in the direction of molecular homology, and vestigial and rudimentary structures. It is particularly gratifying to see a reminder "Evolution is still at work!" with a brief treatment of the medical and agricultural relevance of evolution.

Then natural selection is presented with a fictitious but realistic example. (The example involves adaptive melanism in a population of mice living on white and black sand beaches; a well-documented example of adaptive melanism involves a population of rock pocket mice, *Chaetodipus intermedius*, living inland on light substrate and dark lava.) The example is vivid and helpful, although it is awkward that the inheritability of the mice's coloration is not initially mentioned: the reader is told only, "After a while, almost all the mice were light," without any indication that the shift is generational (p. 52). The oversight is rectified on the following page—"nature selects, or chooses, which living things survive to pass on their traits to their babies" (p. 53)—but then it is necessary to reread the previous discussion.

The discussion of natural selection is presented under the heading "How Does Evolution Work?" as if natural selection were the only process at work in evolution, which is inconsistent (since endosymbiosis is described earlier in the book) and inaccurate: describing natural selection as important would have been preferable. In any case, the discussion of natural selection is followed by a discussion of artificial selection. The order of explanation thus inverts that of the *Origin*, which introduces natural selection by first describing artificial selection, with which Darwin's original readers were presumably more or less familiar. With increased urbanization, Cole and Degen's readers are not so likely to be acquainted with artificial selection, so the point of discussing it (at the same length as natural selection) is obscure.

Given the continuing popularity of the Magic School Bus franchise—including not only the books but also a number of video games, two television series, and, reportedly, a planned big-screen version with Elizabeth Banks as the beloved teacher—the book is sure to end up in the hands of children across the country. Wahoo! (as Ms. Frizzle would say). Asked in 2019 by *PBS Newshour* why she and Degen wanted to write a book about evolution, Cole replied, "A famous scientist [Theodosius Dobzhansky, writing in *The American*

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Biology Teacher] once said, 'Nothing in biology makes sense except in the light of evolution.' That really means that evolution is the story of life on Earth." For anyone wanting to share that story with young readers, *The Magic School Bus Explores Human Evolution* will be a splendid start.

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DISTINGUISHED SERVICE AWARD ... NABT members and friends are invited to nominate outstanding scientists, science communicators, and educators to receive the NABT Distinguished Service Award. The award was established in 1988 to commemorate the 50th anniversary of the Association, and nominees should be nationally recognized for major contributions to biology education through their research, writing, and/or teaching. Recipients are honored at the NABT Professional Development Conference.

PROF. CHAN TWO YEAR COLLEGE AWARD FOR ENGAGED TEACHING OF BIOLOGY ... Sponsored by Sarah McBride and John Melville, the Professor Chan Two-Year College Award for the Engaged Teaching of Biology is given to a two-year college faculty member who has successfully developed and implemented pedagogical approaches that are engaging, creative, and inclusive and has disseminated these practices within and/or beyond their institution. This award includes $500 toward travel to the NABT Professional Development Conference, a plaque to be presented at the conference, and one-year complimentary membership to NABT. The nomination deadline is **May 1, 2022.**

ECOLOGY/ENVIRONMENTAL SCIENCE TEACHING AWARD ... Sponsored by Vernier Software & Technology, the Ecology/Environmental Teaching Award is given to a secondary school teacher who has successfully demonstrated an innovative approach in the teaching of ecology/environmental science and has carried that commitment to the environment into the broader community. Vernier's sponsorship of this award includes up to $500 toward travel to the NABT Professional Development Conference, and Vernier equipment. The recipient also receives a plaque to be presented at the NABT Professional Development Conference and a one-year complimentary membership to NABT. The nomination deadline is **March 15, 2022.**

EVOLUTION EDUCATION AWARD ... The Evolution Education Award, sponsored by BSCS Science Learning and NCSE, recognizes innovative classroom teaching and community education efforts to promote the accurate understanding of biological evolution. The award is presented to K-12 and higher education faculty on alternating years. K–12 educators are eligible in 2022. The award includes a combined $1,000 honorarium, a recognition plaque to be presented at the NABT Professional Development Conference, and a one-year complimentary membership to NABT. The nomination deadline is **March 15, 2022.**

FOUR-YEAR COLLEGE & UNIVERSITY SECTION BIOLOGY TEACHING AWARD ... This award, sponsored by NABT's Four-Year College & University Section, recognizes creativity and innovation in undergraduate biology teaching. These innovations may include curriculum design, teaching strategies, and laboratory utilization. Additionally, award winners will agree to present their work during the NABT Conference. The award is open to NABT members and includes $500, a recognition plaque to be presented at the NABT Professional Development Conference, and a one-year complimentary membership to NABT. The nomination deadline is **May 1, 2022.**

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GENETICS EDUCATION AWARD ... Sponsored by the American Society of Human Genetics (ASHG) and the Genetics Society of America (GSA), the Genetics Education Award recognizes innovative, student-centered classroom instruction to promote the understanding of genetics and its impact on inheritance, health, and biological research. The award includes a $1000 honorarium, a recognition plaque to be presented at the NABT Professional Development Conference, and one year of complimentary membership to NABT. The nomination deadline is **March 15, 2022.**

HONORARY MEMBERSHIP ... The highest honor bestowed by NABT, this award recognizes individuals who have "achieved distinction in teaching, research, or service in the biological sciences" as Honorary Members. Those selected become lifetime members of the Association and receive recognition in NABT publications and at the NABT Professional Development Conference. Nominations may be made by any NABT member and must include (1) a description of the candidate's qualifications, (2) a detailed biographical summary, and (3) supporting letters from at least nine NABT members. The nomination deadline is **March 15, 2022.**

JENNIFER PFANNERSTILL TRAVEL AWARD ... Established to honor the memory of Jennifer Pfannerstill, this need-based scholarship provides support for a teacher who has successfully demonstrated a commitment to developing as a professional by attending the NABT Conference for the first time. The award is supported by a contribution from Bedford, Freeman, and Worth as well as private donations, and the recipient will receive registration to the NABT Professional Development Conference, hotel accommodations for the duration, travel reimbursement, and a one-year complimentary membership to NABT. The scholarship is open to teachers at all levels, but nominees must be current NABT members. The nomination deadline is **March 15, 2022.**

KIM FOGLIA AP BIOLOGY SERVICE AWARD ... The Kim Foglia AP Biology Service Award recognizes an AP Biology teacher who displays a willingness to share materials, serves as a mentor to both students and professional colleagues, creates an innovative and student centered classroom environment, and exemplifies a personal philosophy that encourages professional growth as an AP biology teacher. Sponsored by Pearson and the Neil A. Campbell Educational Trust, the Kim Foglia AP Biology Service Award includes a $1000 honorarium, a recognition plaque to be presented at the NABT Professional Development Conference, and a one-year complimentary membership to NABT. The nomination deadline is **March 15, 2022.**

OUTSTANDING BIOLOGY TEACHER AWARD ... Every year, the Outstanding Biology Teacher Award (OBTA) program attempts to recognize an outstanding biology educator (grades 7-12) in each of the 50 states; Washington, DC; Canada; Puerto Rico; and overseas territories. Candidates for this award must have at least three years public, private, or parochial school teaching experience. A major portion of the nominee's career must be devoted to the teaching of biology/life science, and candidates are judged on their teaching ability and experience, cooperativeness in the school and community, and student-teacher relationships. OBTA recipients are special guests at the Honors Luncheon during the NABT Professional Development Conference; receive gift certificates from Carolina Biological Supply Company, materials from other sponsors, and award certificates and complimentary one-year membership to NABT. **The nomination deadline varies by state.** Please contact NABT at awards@nabt.org for more details.

OUTSTANDING NEW BIOLOGY TEACHER ACHIEVEMENT AWARD ... This award, sponsored by Pearson and the Neil A. Campbell Educational Trust, recognizes outstanding teaching (grades 7-12) by a "new" biology/life science instructor within their first three years of teaching (when nominated) who has developed an original and outstanding program or technique and made a contribution to the profession at the start of their career. The award includes a $1,000 honorarium, recognition plaque to be presented at the NABT Professional Development Conference, and a one-year complimentary membership to NABT. The nomination deadline is **March 15, 2022.**

THE RON MARDIGIAN BIOTECHNOLOGY TEACHING AWARD ... The Ron Mardigian Biotechnology Teaching Award, sponsored by Bio-Rad Laboratories, recognizes a teacher who demonstrates outstanding and creative teaching of biotechnology. The award is given to secondary school teachers in even numbered years, college/university instructors in odd numbered years. The award may be given for either a short series of activities or a long integration of biotechnology into the curriculum. The award is presented at NABT's Professional Development Conference and includes a recognition plaque, a one-year complimentary membership to NABT and up to $500 toward travel to the NABT Professional Development Conference and Bio-Rad materials. The nomination deadline is **March 15, 2022.**

TWO-YEAR COLLEGE BIOLOGY TEACHING AWARD ... Sponsored by NABT's Two-Year College Section and Cell Zone, Inc., this award recognizes a two-year college biology educator who employs new and creative techniques in their classroom teaching. The primary criterion for the award is skill in teaching, although serious consideration is given to scholarship, curriculum design, or laboratory utilization. Nominees must be current members of NABT. The award includes $500 toward travel to the NABT Conference, a recognition plaque to be presented at the NABT Professional Development Conference, and a one-year complimentary membership to NABT. The nomination deadline is **May 1, 2022.**

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CLASSROOM MATERIALS & MEDIA REVIEW

JEFFREY D. SACK, DEPARTMENT EDITOR

Yellow Scope Science Kits for Girls (https://yellow-scope.com)

Studies have shown that up to third grade, boys and girls are equally interested in science. However, by middle school, girls tend to lose that enthusiasm while boys continue to develop it. As this trend continues throughout their academic careers, women end up making up more than half the workforce but fill only a quarter of the science and technology jobs.

Many publishers and materials providers have tried to appeal to girls by producing "science kits" for them. However, an analysis of these kits finds that most come in sparkly boxes, are loaded with colorful stickers, and have the participants make crafts, makeup, or perfume. Now, while there is nothing wrong with this, these kits do not expose their intended audience (young girls) to real science. To fill this much-needed gap, a pair of "science moms" have developed an exciting collection of authentic science kits that expose participants to real science experiences: making predictions, collecting data, and drawing conclusions.

Yellow Scope Science Kits for Girls is a collection of boxed science kits that include topics such as DNA & Traits; Acids, Bases, & pH; and Paper Chromatography (there is also a chemistry-focused kit called Beakers & Bubbles). Each of these self-contained kits comes with almost everything a student will need to perform an actual experiment.

For example, the DNA & Traits kit, which involves extracting DNA from strawberries, includes a work mat, plastic beakers, a dropper, solution bottles, chalk, stickers, data sheets for several trails, a sieve, and a flashlight. Due to safety and shipping regulations, the only things missing are the consumables (the alcohol, soap, and fruit).

Before starting the activity, students need to read through the lab manual, which not only details the steps of the DNA extraction but also provides a plethora of age-appropriate background about what DNA is and why it is important. The students are then guided, step-by-step, through removing the DNA from the fruit cells and then observing it in the beaker.

The second part of the DNA & Traits activity has students investigating actual genetic traits. The background in the lab manual connects the concepts of DNA and traits and then shows how they apply in the real world. Students are given a data sheet with several genetic traits listed. They are instructed to survey their family and friends to see how many of them express each trait. They then calculate percentages of individuals with each trait.

In the third part of the DNA & Traits activity, students use DNA codes to determine the traits of a monster. They use a "monster traits key" to randomly select the genetic code of the monster's body from a provided list of codes. They repeat the process for eyes, mouth, and spots. They then use the enclosed stickers and craft materials to construct a model of what their monster looks like.

The other kits from Yellow Scope are designed the same way and have the same level of scientific thinking involved. While the subject matter offerings are somewhat limited at the moment, there are activities in environmental science and food science in development. Each kit comes in its own box, but the company has also put together classroom packs of 10 or 25 for larger groups. Yellow Scope Science Kits are designed to do at home, under adult supervision. However, with the addition of the classroom packs, the activities and experiments can easily be performed in a classroom.

While specifically created to entice girls ages 8–12 into science, the activities are not gender specific and boys will enjoy them just as much. Elementary and middle school parents and teachers can use the activities and experiments within the kits to teach new concepts, or to enhance other learning. The DNA & Traits kit is specifically for biology, but the Paper Chromatography and Acids, Bases, & pH kits could easily be adapted to show how these ideas are related to life science.

Getting, and keeping, girls interested in science is essential in today's climate. Yellow Scope Science Kits do a great job of catering to girls (and boys too) to help keep them interested as they move through their schooling.

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